AN ABSTRACT OF THE THESIS OF

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Dr Larry Boersma

Rates of germination and emergence of corn were measured as influenced by soil physical parameters using blotter paper and a sandy loam soil as growth media. The corn seeds used were a hybrid of Funk's (DJ7xLH93).

Experimental conditions were soil temperature of 20°C, 25°C, 30°C, and 35°C, soil water potential of -33, -100, -500, and -1000 kPa, soil bulk density 1.29 and 1.36 Mg/m^3 and seeding depth of 3 and 7 cm.

For the germination experiment seeds were put in contact with polyethylene glycol at solution concentrations to produce the desired water potentials. Treatment temperatures were maintained in a growth chamber and germination was evaluated every twelve hours.

The number of hours required to obtain 50 and 80% germination was significantly increased by lowering either temperature or water potential. Although significant interactions were measured, temperature and water potential affected germination in different

ways. Time to attain 80% of germination decreased as temperature increased until the optimum of 30°C was reached. Decreased osmotic potential levels progressively delayed and reduced germination. Time to germination increased greatly below -500 kPa.

For emergence experiments seeds were planted in soil packed in covered containers which were placed in a growth chamber. Effects of soil temperature, soil water potential, bulk density, and seeding depth were evaluated. Bulk densities of 1.29 and 1.36 Mg/m^3, were achieved by no compaction and compaction. The two seeding depth were 3 and 7 cm.

Time needed for emergence was influenced by soil temperature more than by any other variable. The time for emergence decreased progressively with lowering of soil water potential, lowering temperature or with increase in seeding depth. No significant differences resulted from increasing bulk density.

In both the germination and emergence experiments, changes in temperature were more important than changes in water potential at high water potential. However this relation was reversed at water potentials lower than -500 kPa, where changes in water potential were more important than changes in temperature. The minimum time for both germination and emergence occurred at 30°C, at all water potentials.

Effect of seeding depth was more important than effect of bulk density for time to emergence. Increases in time were between 20-30% as the seeding depth increased from 3 to 7 cm.

Compaction began to limit seedling emergence at 1.44 Mg/m3.

GERMINATION AND EMERGENCE OF CORN (ZEA MAYS, L) AS A FUNCTION OF SOIL PHYSICAL PARAMETERS

by

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In memory of my sister:

Dr Ruby E. Sanchez, M.D.

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GERMINATION AND EMERGENCE OF CORN (ZEA MAYS, L.) AS A FUNCTION OF SOIL PHYSICAL PARAMETERS

I. INTRODUCTION

Corn is one of the most important food crops in the world today, and demand for corn is increasing due to the continued increase in world population and improving standards of living.

Corn growers often contend with cold and dry soils during spring planting. Frequently, low temperatures and dry surface soil have been found to adversely affect corn germination and consequently plant density (Schneider and Gupta, 1985). Depth of seeding and compactation can also cause problems, particulary when growers must plant corn deeper than normal to place the seed into moist soil (Dasberg, et al., 1966; Alessi and Power, 1971). Rapid and complete germination and emergence improve the chance for obtaining a good yield.

Under dryland conditions it can be very difficult to obtain an optimum plant density, because seed germination is controlled primarily by soil physical parameters which can vary widely at a given time or from year to year (Harper and Benton, 1966).

Soil water potential and soil temperature control seed germination and emergence either through effects on water uptake during imbibition or by affecting the rates of metabolic reactions which produce activation of numerous enzymes and physiological processes during embryonic development and seeding growth (Ehrler and Gardner, 1971).

However, germination and emergence also is controlled by physical impedance of the soil, primarily compaction and seeding depth (Phillips and Kirkham, 1962).

These experiments were preceded by a review of the literature, where different authors used different units. I have decided to report the units used for each author without changes.

The objective of this study was to develop and evaluate relationships to describe the combined effect of these soil physical parameters.

II. LITERATURE REVIEW

Many investigators have studied the influence of soil parameters on germination processes. According to Heydecker (1972), the main environmental factors that affect the germination rate and total germination percentage of cereals are the following:

1) the temperature at which germination occurs,

2) the amount of water present,

3) the position of the embryo relative to the level of oxygen present in the germination medium,

4) the level of infestation by micro-organisms,

5) the presence of dissolved ions in the germination medium,

6) the number of pre-germinated seeds present,

7) the length of time seeds were stored at high temperatures,

8) the water content of the seed during the storage.

Schneider and Gupta (1985), who studied the effects of soil physical parameters on corn emergence (Zea mays L.), indicated that environmental factors of critical importance to corn growth between planting time and emergence were soil temperature, soil water content, nutrients and physical condition of the seed bed.

According to Kaufmann and Ross (1970), environmental stresses, primarily soil water content and extreme temperatures restrict successful seed germination and plant establishment in the arid and semi-arid regions. However, quantitative relationships between the effects of soil temperature, soil water content, planting depth and emergence time have not been adequately defined. Factors affecting crop establishment such as soil temperature, moisture, and planting depth may vary widely between years or location in any one field, making it difficult to predict the rate and extent of plant emergence based exclusively on planting date (Willis, et al. 1957).

Genetic constitution related to germination and emergence

Maize endosperm is triploid and the alteration of a single gene can determine seedling survival during germination. Heydecker (1972) showed that the germination capacity of maize decreased as the proportion of the sugary allele called (Su) in the endosperm decreased. The variation in germination percentage ranged from 46% to 93%, according to the proportion of (Su), (genotype constitution). The author found that of six genes in maize, two (2 and 4) were associated with decreased viability and decreased vigor during emergence.

Characteristics of germination in maize are partially governed by genetic controls. The particular present pattern of behavior of the seeds either in a cultivated or wild species is likely to have been the result of selection (Heydecker, 1972). According to Koller (1964) cited by Heydecker:

> "The nature of many germination - regulating mechanisms in seeds lends itself to an interpretation in terms of survival value for the species. This, however is no more than an indication, and direct experimental evidence is needed regarding the role played by the entire germination - regulatory equipment of the seeds in relation to the spectrum of combinations of variables which make up the environmental complex."

Influence of soil water potential and soil temperature on seeds

Soil water potential and soil temperature are important environmental factors affecting seed germination. Individually each factor has been studied rather extensively, but little is known about the effects of water stress at different temperatures.

Conclusions about the effects of water stress at one temperature are not valid at other temperatures if a water stress-temperature interaction exists (Van de Vender and Grobbelaar, 1985).

Soil water potential

The imbibition process is governed by a transport equation, which for water is most conveniently written as follow:

$$F = - K\ (d\psi/dx), \qquad (1)$$

where F is the flux, K is the hydraulic conductivity and $d\psi/dx$ is the potential gradient across a given distance. This flux equation can be written in terms of diffusivity as follows:

$$F = -D\ (d\theta/dx), \qquad (2)$$

where D or diffusivity is equal to the product of the hydraulic conductivity K and the slope of the soil water characteristic curve ($d\psi/d\theta$), and θ is the volumetric water content (Hillel, 1982).

Quantitative analysis of water uptake during the imbibition stage assumes a spherical seed of a mean radius r (cm), mean diffusivity $\overline{D}$ [cm^2/day], and an initial volumetric water content θi (cm^3/cm^3) at time T = 0.

The flux of water from the soil to the seed exterior to the seed interior is described by the diffusive flow equation:

$$d\theta/dt = (\bar{D}/r)(d^2(r \,.\, \theta)/dr^2) \qquad (3)$$

where θ is the volumetric water content at time T (Hadas and Russo, 1974). However, this equation can also be written as follows (Hadas, 1969).

$$d\theta/dt = \bar{D}\ \Delta^2\ (\theta) \qquad (4)$$

where Δ^2 is the second derivative of θ in relation to the spherical coordinates.

From equations (3) and (4) it is possible calculate time to imbibition considering the following conditions:

(a) The soil moisture status limits water transfer to the seeds (soil conductivity controls).

(b) Partial contact between the seed and the surrounding media limits the water transfer to the seeds (area of transfer is limited).

(c) Partial contact and comparatively impermeable seed cover limits the water imbibition (seed conductivity and limited area of transfer control).

Most of the cases could be calculated, solving for diffusivity in equation (4), and then calculating cumulative water uptake using the following equation:

$$M/M\infty = 1 - 6/\pi^2 \sum_{n=1}^{\infty} (1/n)^2 \exp \{-(n^2 \pi^2 . \bar{D}t/r^2)\} \qquad (5)$$

where M = cumulative water uptake at time t, M∞ = final value of the cumulative water uptake (equilibrium), r = radius from the seed center, and n = integers (1, 2, 3,..., n) which represent the number of sheets of thicknesses L1, L2,..., Ln and diffusion coefficients D1, D2,...,Dn in a composite membrane.

Mean diffusivity (D) is calculated by using the equation:

$$\bar{D} = (1.85/\theta^{1.85}) \int_{\theta_0}^{\theta i} (\theta_i - \theta)^{0.85} D(\theta)\, d\theta \qquad (6)$$

where θi represents the initial volumetric water content, D = water diffusivity at a given θ, and 1.85 and 0.85 are constants.

Results obtained using these quantitative analysis techniques show that even when the partial contact is minimal and the diffusivity is low, the seeds may be able to take up to 90% of their water needs in less than a day.

Considering vapor transfer alone with a drastically reduced diffusion coefficient, the time for imbibition is still very short. In this case the solution for equation (4) is given by equation (7) (Hadas, 1969)

$$M/M\infty = 1-(6/\pi^2(a^2+ab+b^2)) \sum_{n=1}^{\infty} (b \cos n.\pi - a/n)^2$$

$$\exp-(n^2\pi^2 \bar{D}.t/(b-a)^2) \qquad (7)$$

where (a) is the distance from the seed center to the seed coat and (b) is the same distance, including the seed coat.

soil water potential and germination

Hadas and Russo (1974) studied water uptake rates, seed diameter, and time of germination. They calculated the contact area between seed and soil of the chickpea, pea, and vetch seeds.

Different sand fractions were used in this experiment, ranging from 0.6 mm to 4 mm particle size. The seed beds were brought to equilibrium water contents in pressure cells with matric pressures from -0.1 to -15 bars. The uniform depth of seedlings was 5 cm for all treatments. They defined germinated seeds as those from which a radicle of 2mm or longer had emerged.

The results indicate that the coarser the soil texture becomes, the smaller the relative wetted area is for any given seed size and soil water matric potential.

The authors also concluded that the seed-soil contact impedance, which is defined in terms of resistance to water uptake, increased as the wetted seed area and/or soil hydraulic conductivity decreased as a consequence of changes in seed-soil interface.

Pawloski and Shaykewich (1972), determined germination rate of wheat at several water potentials (-0.8, -5.3, -7.8 and -15.3 bars) and at constant temperature of 20°C, using a system in which a lens of soil is brought to a predetermined potential by use of osmotic solutions.

In Figure 1, accumulated percent germination is plotted as a function of time. There was a gradual decrease in germination rate with decreasing water potential. The germination rate was slower at the 15 bar tension, than at lower tensions, but the final germination percentage was the same.

Williams and Shaykewich (1971) worked on the influence of soil matric potential and hydraulic conductivity on the germination of rape (Brassica napus L.) seeds. Comparative studies in three seed-soil water systems were made. The response pattern was similar for each system. A slight decrease in soil water potential (from -0.6 to -2.8 bars) produced a small increase in time required for germination but reducing water potentials to less than -10 bars resulted in a dramatic reduction in the rate of germination and no germination occurred after 15 days at -15 bars. Hydraulic conductivity of all segments of the path affects water uptake and consequently germination. Here, change in hydraulic conductivity of the soil system was demonstrated to be a limiting factor in the germination process. The data obtained by these authors show that the seed water content decreased significantly with decreasing soil matric potential treatments.

It was demonstrated that the initial driving force for water movement between soil and seed is considerable and despite high resistance in the seed tissue, absorption in the first three hours is fast enough to cover the seed water requirements.

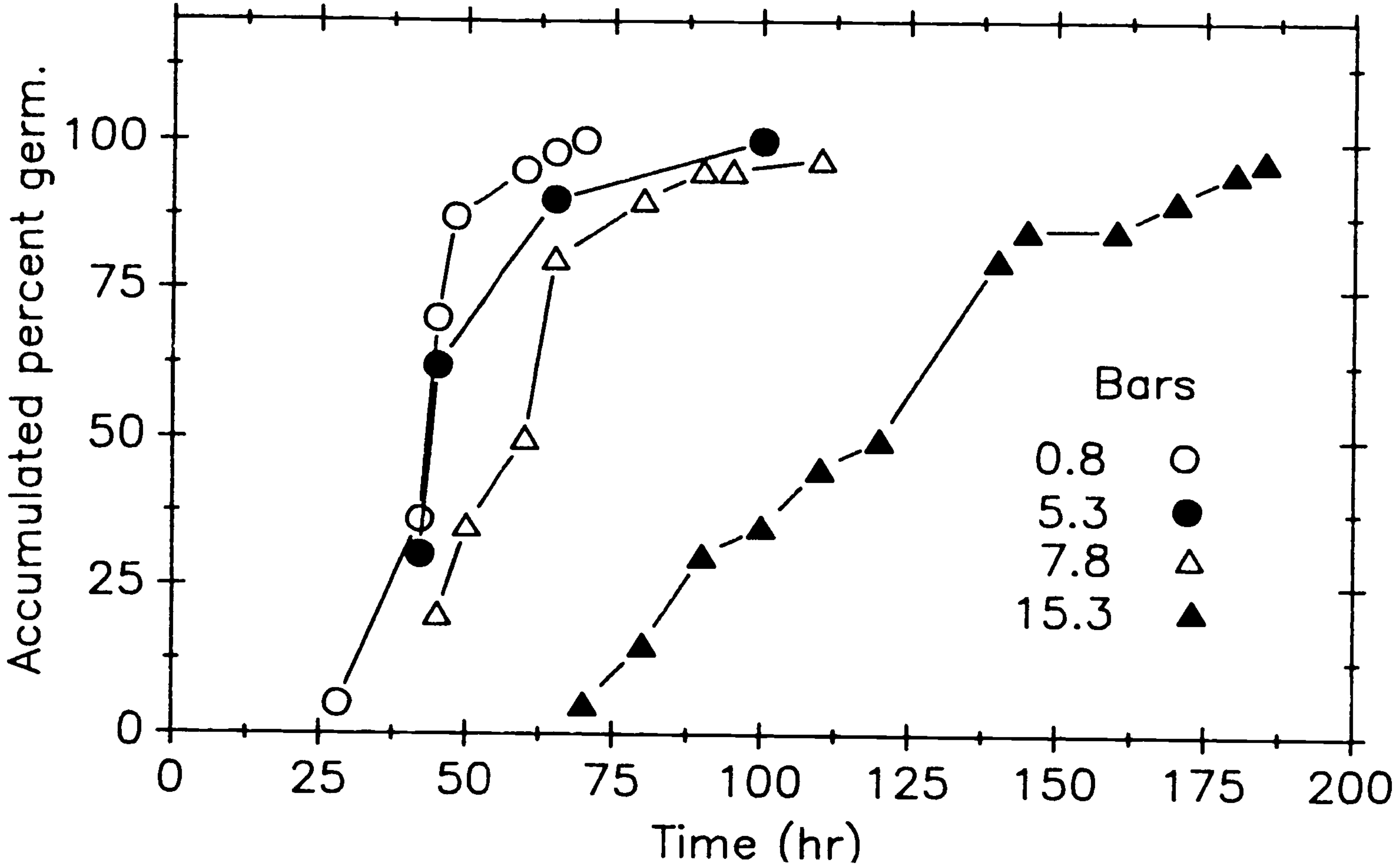

Figure 1: Accumulated percent germination as a function of time for different soil water potentials. Temperature was constant at 20°C (Pawloski and Shaykewich, 1972).

Collis - George and Hector (1966) investigated the relationship between soil matric potential and contact area, considering the influence of the geometry of the area. These authors suggest that based on the experiments of Sedgley (1963), matric potential is the main cause of regulation of wetted contact area of seed and medium. The lower the soil matric potential, the smaller the contact area.

On the other hand, Sedgley has presented results which relate the influence of matric potential and germination speed, based on experiments with seeds placed within water columns under tension of 1 or 200 cm, and recording time to germination.

These results are based on the action of compression and decompression of water on the seed and show that if a film of water encloses the seed, the seed and medium are subject to an isotropic compressive stress. This compression action is numerically equivalent to matric potential. Under tension, where matric potential is lower the effect will be of an isotropic decompression causing the seed to dilate slightly and in consequence germinate quicker than in free water.

Despite these contradictory results between contact area, matric potential and germination speed, Collis-George (1966), concludes that matric potential and germination are related by the following:

1) the direct effect of energy on water uptake by the seed,
2) the indirect effect of controlling wetted area,
3) the indirect effect of controlling the strength of the soil and the compression of the seed.

Soil temperature

Soil temperature influences germination and emergence both directly and indirectly, directly by affecting the rates of metabolic reactions and indirectly by influencing the energy level and transport of water in the soil system (Halitligil, 1975).

Critical maximum and minimum temperatures are the boundaries where germination takes place as a consequence of metabolic reactivation.

Low temperatures influence germination and seedling emergence by slowing water transport as a result of the increase of both the viscosity and surface tension of water.

Heydecker (1972), studying germination response to temperature in many species found that responses span a wide temperature range from about 5°C to 35°C with variations of minimum, maximum and optimum temperatures according to the species. Time to attain 50% of germination was reached over practically the entire range of temperature at which normal metabolic processes occur in plants. Figure 2 shows that the lowest temperature at which 50% of germination of Scabiosa Columbaria was achieved occurred at about 5°C, and the highest at about 35°C. Three different kind of treatments were carried out to determine the effect of diurnal fluctuations: constant temperatures, a mean derived from 5°C diurnal variation, and a mean temperature derived from a 10°C diurnal variation. Results showed that at constant temperatures the maximum temperature for 50% germination was 35°C, with 5°C diurnal fluctuation the maximum was 33°C and with 10°C fluctuation was 32°C.

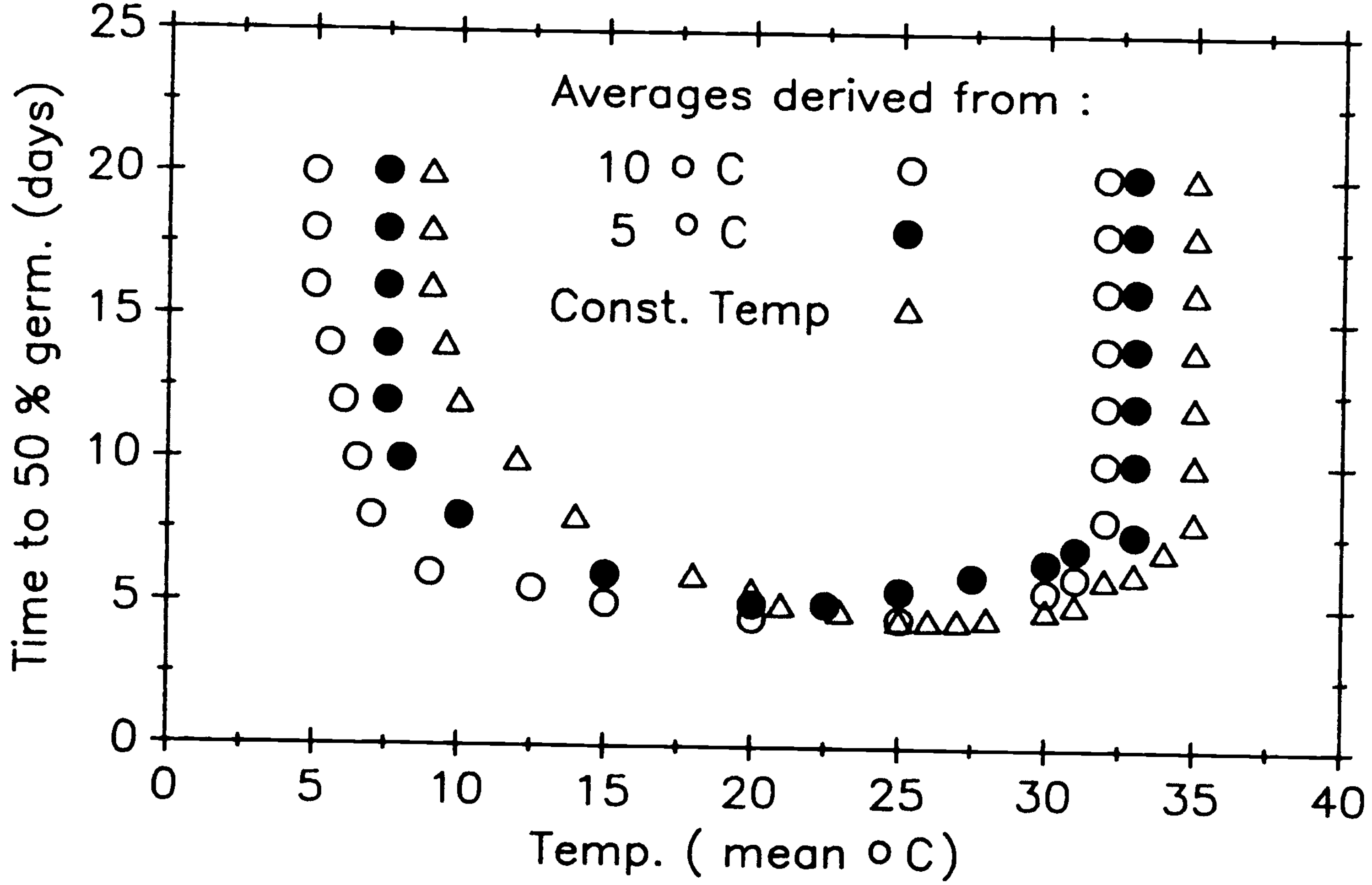

Figure 2: Germination curves for Scabiosa Culumbaria, showing time required to reach 50% germination at constant temperatures and considering averages derived from 5°C and 10°C of diurnal variation (Heydecker, 1972).

Blacklow (1972) studied the influence of temperature on germination and elongation of the radicle and shoot of corn (Zea mays L.). The observations were done by sowing seeds of corn in pots of wet, freely-drained, vermiculite kept in darkened constant temperature chambers ranging from 9.5 to 40°C.

Figure 3 shows that for a given temperature the rate of shoot elongation was lower than radicle elongation and the optimum temperature for elongation of both axes was about 30°C. Almost no elongation occurred below 10°C and a constant temperature of 40°C was lethal. In addition, this figure shows an almost linear relationship between rate elongation and temperature over the range of 10 to 30°C, but a decline in rate when the temperature exceeded 32°C.

In relation to the same experiment, curves in Figure 4 show that initiation of the radicle preceded the shoot for each temperature and both decreased to a minimum at about 30°C. After the initiation a radicle-shoot independence established rapidly and they became spatially separated because of gradients of soil temperature in the field which affect the region of the elongation axes.

The author concluded that the radicle and shoot do not compete for limited substrate but the presence of the radicle promotes shoot growth, due to an effect on the growth regulator balance. The rates of elongation were greatest at about 30°C and effectively ceased at 9 and 40°C.

Soil water potential and soil temperature interactions

Studies evaluating simultaneous effects of more than one

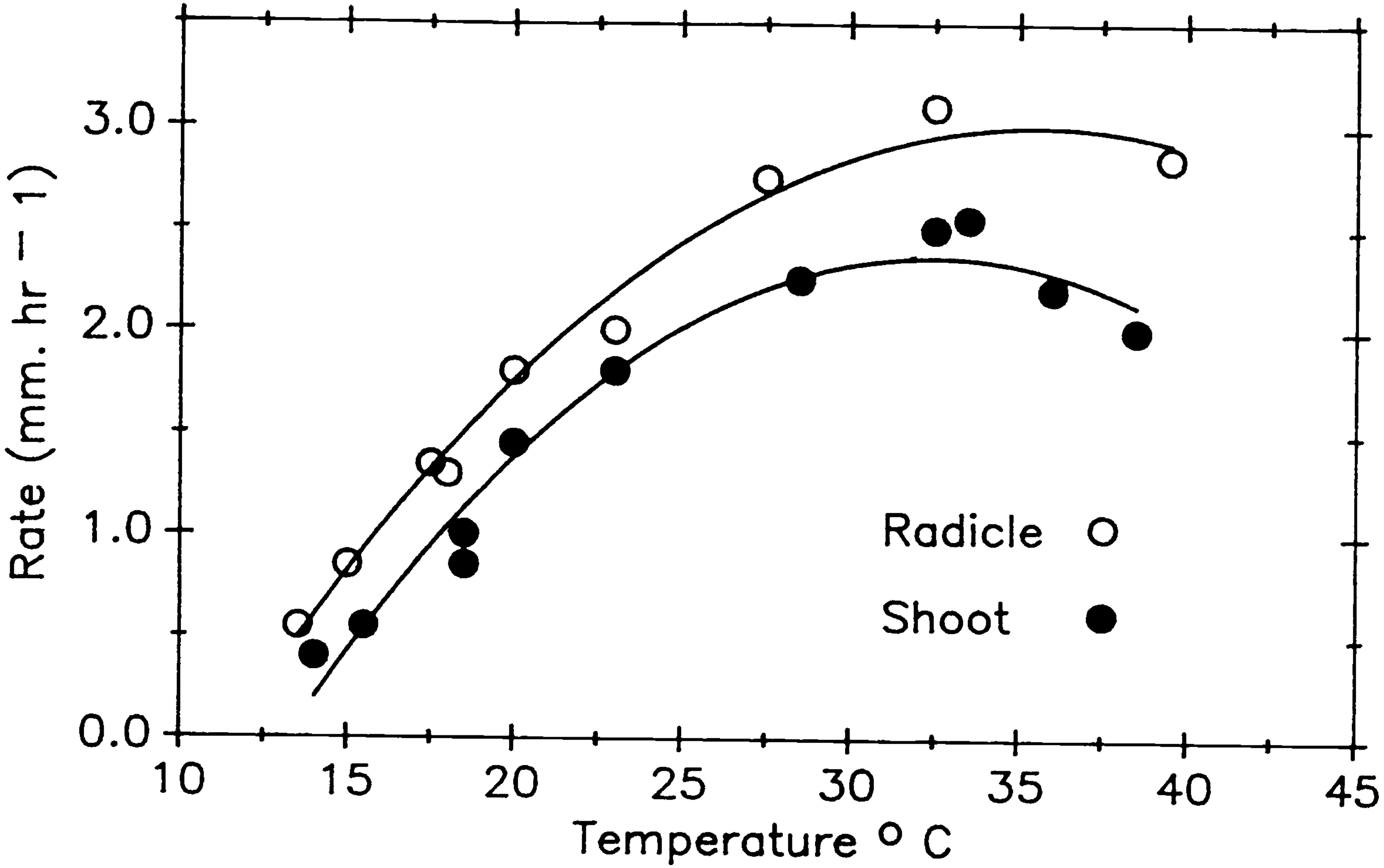

Figure 3: Rates of elongation during the emergence stage of the radicle and shoot of corn as a function of temperature (Blacklow, 1972).

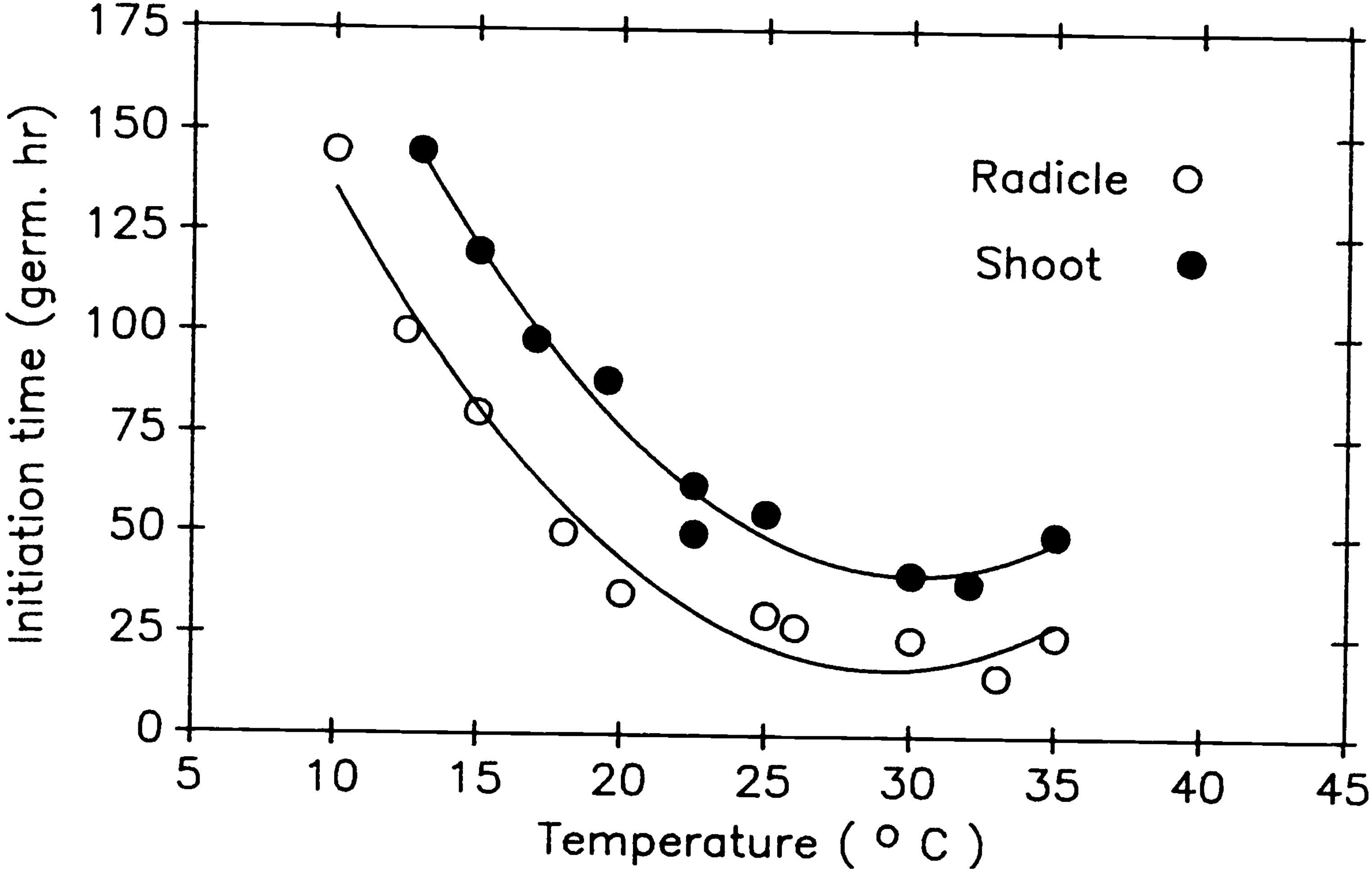

Figure 4: Time to initiation of radicle and shoot of corn as a function of temperature (Blacklow, 1972).

environmental factor on germination are rather scarce. Present studies suggest that the matric effects would be additive to osmotic potential effects and also that these water potential effects would be accentuated by unfavorable high or low temperature.

Sharma (1976), evaluating the interaction between water potential and temperature effects on germination of three semi-arid plant species found that the rate of germination of all the species declined with decreasing water potential. The germination rates increased with increasing temperature but final germination percentages were highest at a intermediate temperature 20°C (Figure 5). Matric potentials of 0, -2, -4, -8, and -15 bars were created by osmotic solutions of polyethylene glycol and the experiments were carried out in incubators using different temperatures ranging from 5°C to 50°C.

All the species withstood lower matric potential in the vicinity of optimum temperature and while higher temperatures (higher than 30°C) were unfavorable for its germination and caused damage to seeds, lower temperatures (lower than 15°C) were also inhibitory but did not cause permanent damage to seeds.

In one of the most recent studies, Schneider and Gupta (1985) used different treatments for corn emergence: four soil temperature ranges, four different soil matric potentials and seven size aggregate distributions were studied in a completely randomized factorial design.

The temperature ranges were 5-15, 10-20, 15-25, and 20-30°C, the matric potentials were -10, -33, -100 and -500 kPa and the aggregate sizes were: 0.5, 1.0, 1.9, 3.6, 5.6, 6.8 and 11.1 mm. The depth of

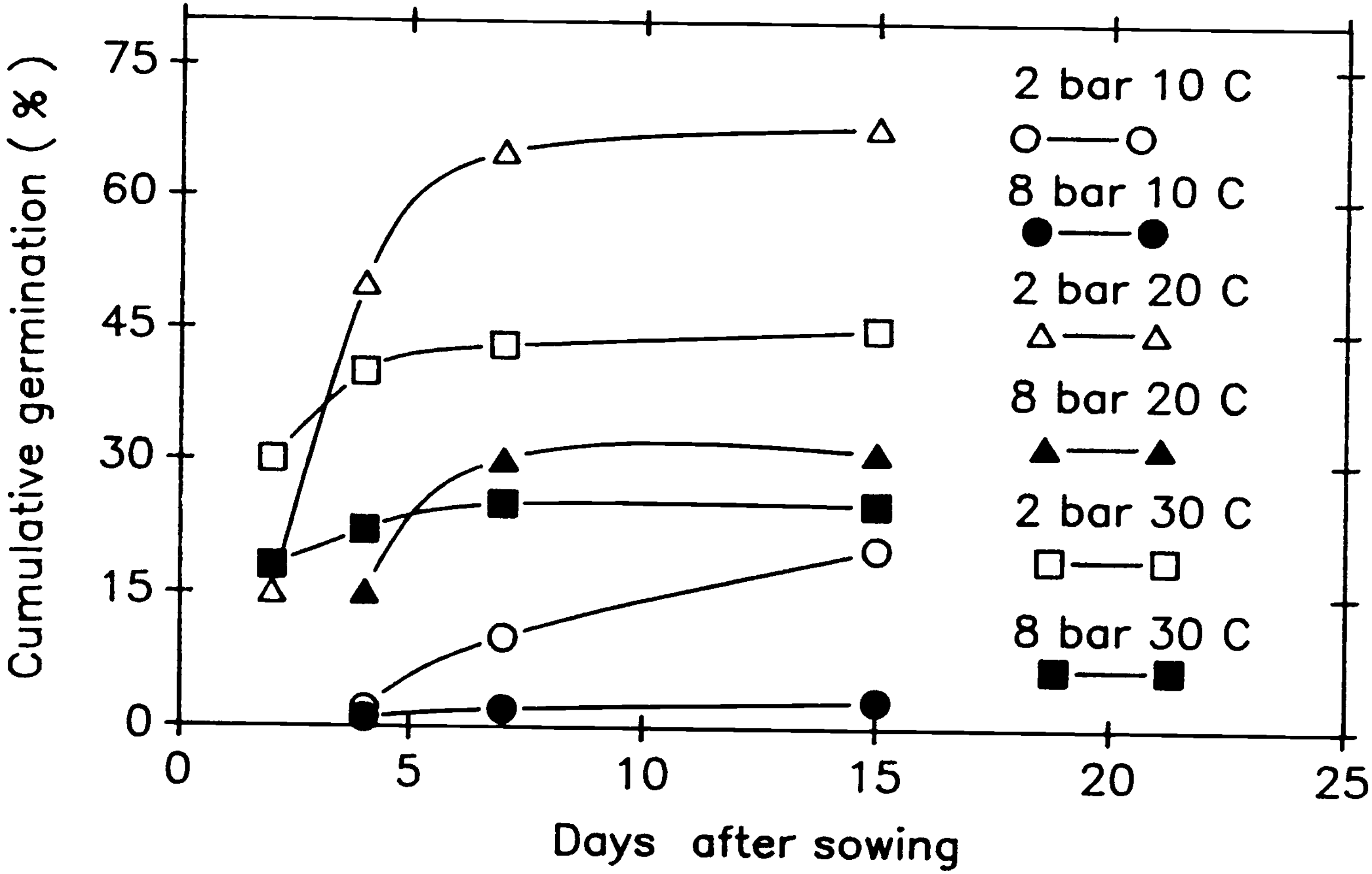

Figure 5: Cumulative germination as a function of time for <u>Danthonia Caespitosa</u> at two levels of matric and osmotic potencial and at three temperatures (Sharma, 1976).

placement was 50 mm in all the treatments. The results indicate that time of emergence was influenced by the independent variables in the following order:

soil temperature
soil matric potential
size of soil aggregates.

Corn emergence was most rapid in the highest temperature range (20-30°C), when the soil was at or above field capacity and the particle size was between 1.0 and 6.8 mm.

According to these authors, germination occurs only after a period of imbibition during which the seed has taken up sufficient water to activate growth. The period of imbibition is controlled primarily by the soil water potential, the hydraulic conductivities of soil and epidermis, and the seed-soil contact area. A seed bed composed of soil aggregates less than 5mm in diameter provided the optimum combination of seed-soil contact and soil hydraulic conductivity for emergence. Emergence was delayed for the largest and smallest aggregate sizes (11.1 and 0.5mm). The delay was caused by a poor soil-seed contact (11.1mm) and the formation of a massive soil clod during water sorption and desorption (0.5mm).

Another experiment of germination and emergence of corn was conducted by Cutforth, Shaykewich and Cho (1985). The focus of their work dealt with soil water - temperature interactions. Two soils were used in determining the soil water characteristic curves by the pressure membrane method. Field capacity (FC) and permanent wilting point (PWP) were calculated from the water content at 33 kPa and 1500 kPa respectively, using the following equations (Shaykewich, 1985):

$$Fc = 8.28 + 0.654 (\theta 33) \tag{8}$$

$$PwP = 0.021 + 0.775 (\theta 1500) \tag{9}$$

Soil and water were mixed to obtain different water contents.

The temperatures were 15, 19, 25, and 30°C and the soil - water mixtures were packed uniformly to bulk densities of 1050 kg/m^3 and 1380 kg/m^3.

The authors used pots where 3 or 4 layers of seeds were sown per pot and covered with soil. Each pot contained 5 to 6 kg of moist soil which was covered to prevent evaporation and opened twice daily for aeration purposes. The results indicate that a decrease in either temperature or water content increased time to germination. For each given temperature, germination times increased with decreasing volumetric water content (θ).

Bulk density and soil water potential in relation to emergence was also evaluated. Days for reaching the 50 and 80 percent germination points were measured. Results, showed that changes in temperature affected germination much more than changes in water potential.

Soil texture and bulk density affected the time required for seedling emergence. Soils with higher bulk densities had longer emergence times because of the soil strength. According to Cutforth, (1985) after a seed is placed in contact with water, water diffuses toward and into the seed because of energy level difference between moist soil and dry seed. The time required for this process to occur depends upon plant species, composition of the seed, permeability of the seed coat and availability of soil water.

Figures 6 and 7 show that at a given water content time to corn germination decreased exponentially with an increase in soil temperature. This relationship between time to germination and temperature can be described by the regression equation:

$$\ln G = a - b\ (\ln T), \tag{10}$$

where a and b are coefficients, T temperature and G time to germination (Schneider and Gupta, 1985).

These curves are steeper at low water content which reach the optimum temperature (lowest germination time), before those of higher water content. After the optimum temperature, time to germination begins to increase again.

Carroll clay loam (Fig 6) had longer germination times than Almassippi loamy sand (Fig 7) for similar soil water contents and temperatures due to a differential level of energy, at the same soil water content and consequently different availability.

Figures 8 and 9 show that time to germination decreases as soil water content increases.

In the case of Almassipi loamy sand at a soil temperature of 25°C, (Fig 9) germination was delayed by 37 hours as soil water content decreased from 0.22 to 0.09 m^3/m^3. At the soil temperature of

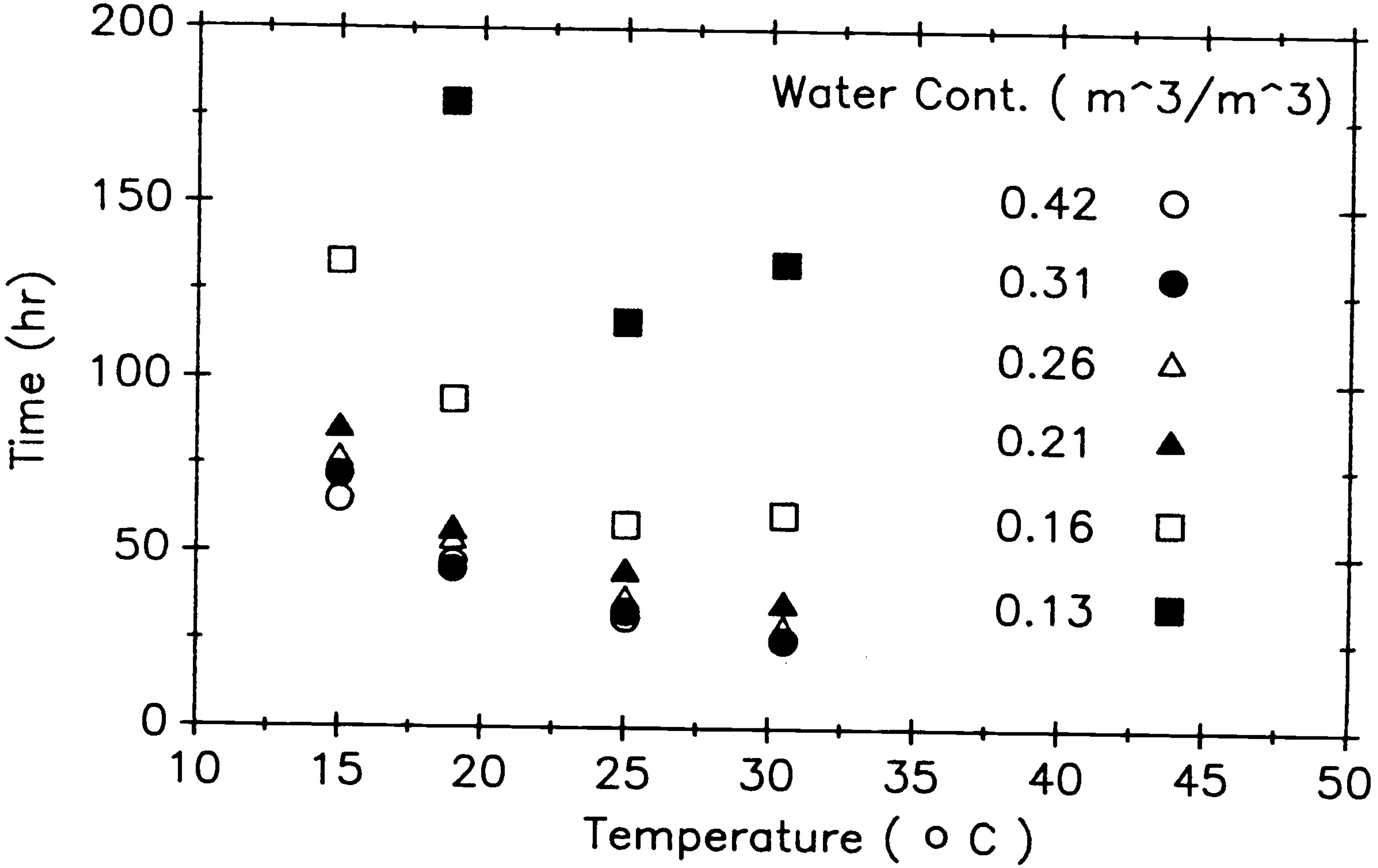

Figure 6: Time in hours to 50% germination as a function of volumetric water content and temperature in a Carroll series clay loam for Pioneer hybrid 3995 (Cutforth, et al. 1985).

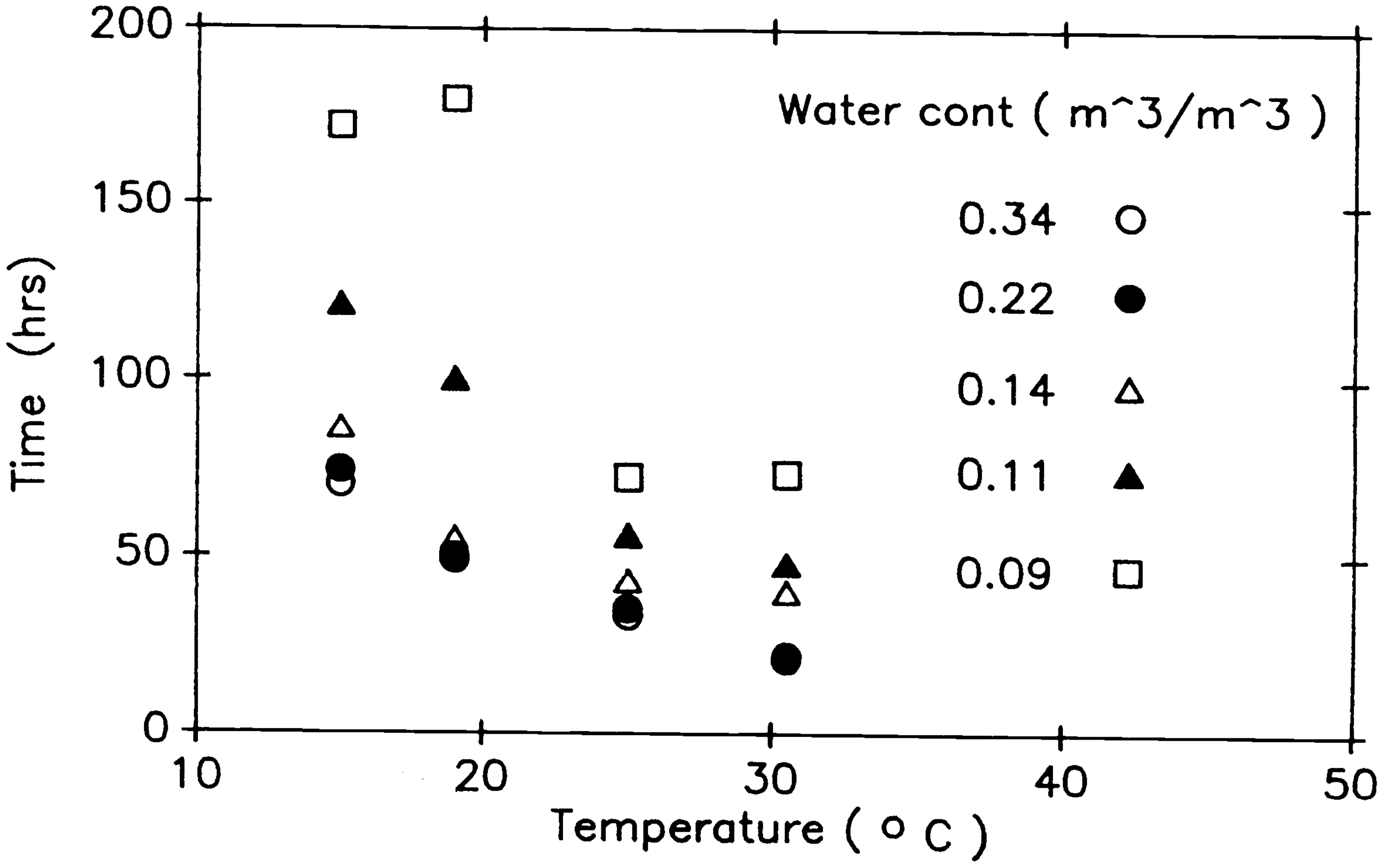

Figure 7: Time in hours to 50% germination as a function of volumetric water content and temperature in an Almasippi series loamy sand for Pioneer hybrid 3995 (Cutforth, et al. 1985).

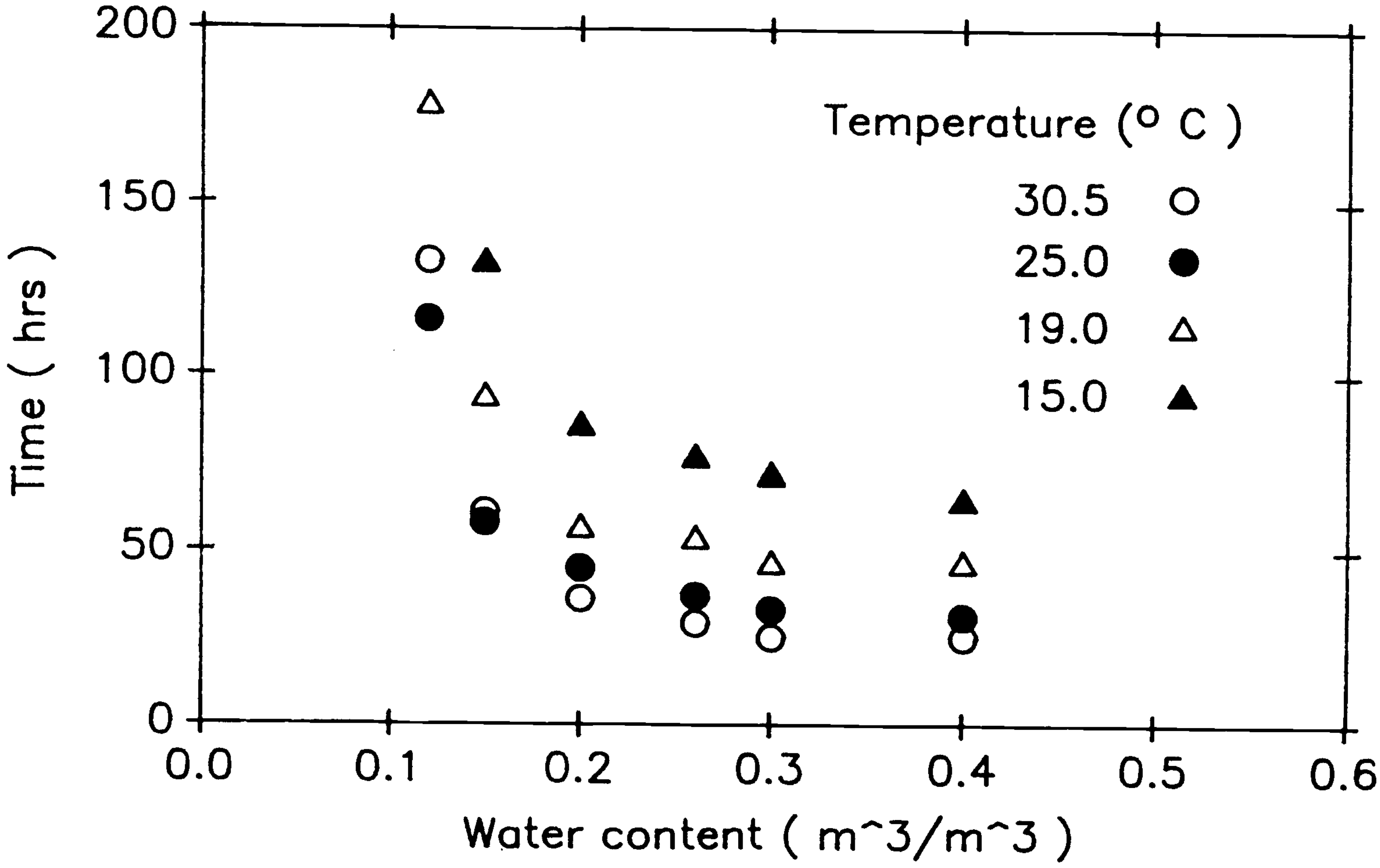

Figure 8: Effect of water potential at different temperatures on 50% of germination of corn Pioneer 3995 in a Carroll series clay loam (Cutforth, et al. 1985).

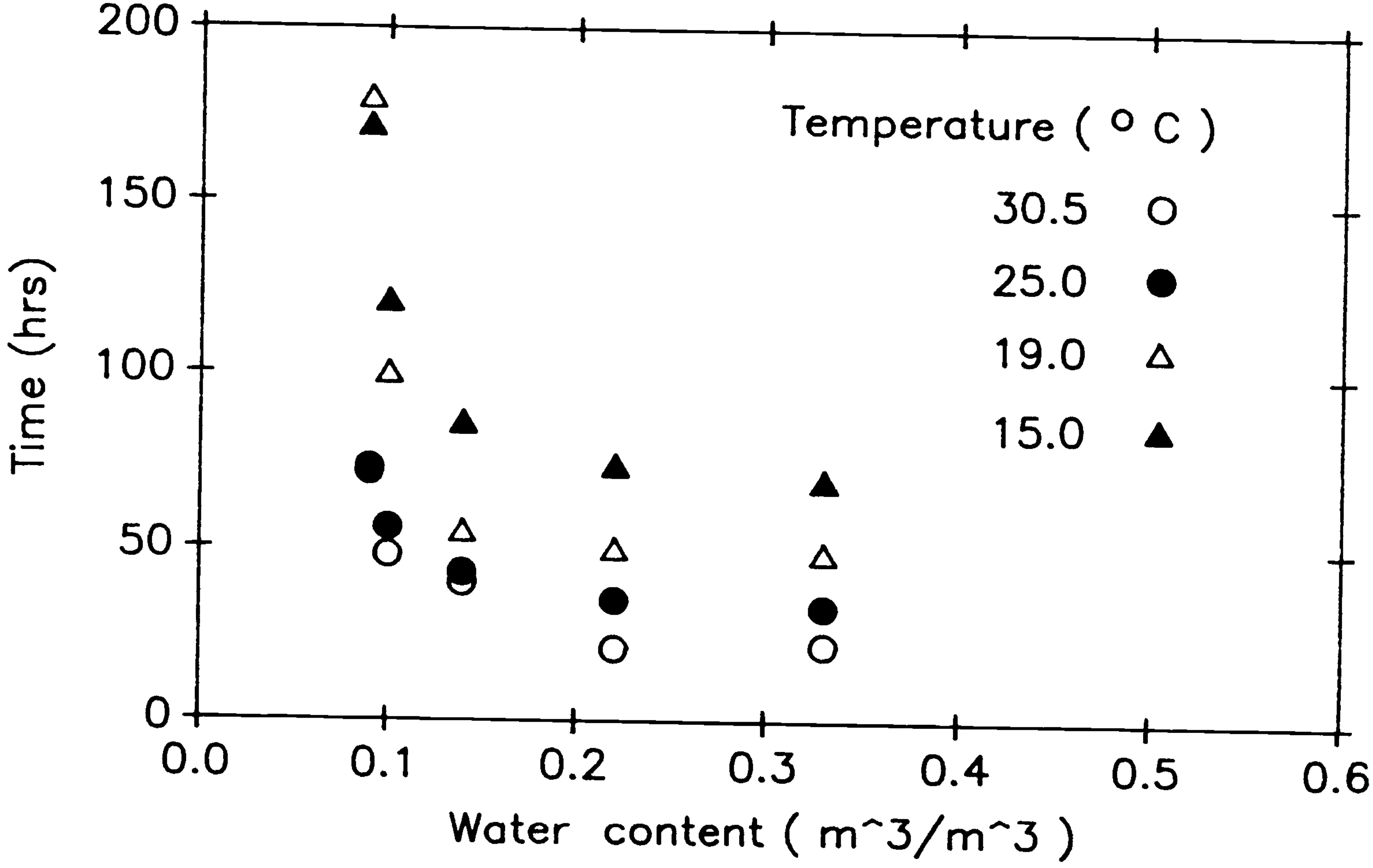

Figure 9: Effect of water potential at different temperatures on 50% germination of corn Pioneer 3995 in an Almasippi series loamy sand (Cutforth, et al. 1985).

15°C, the effect on time to germinate was approximately doubled.

Time to germination was generally more affected by a change in soil temperature than by a change in soil water potential (Halitligil, 1975; Schneider and Gupta, 1985).

The regression equation that describes the relationships between soil temperature, soil water potential, and germination time, can be written as follows:

$$\text{Ln } G = a - b_1 \ln T + b_2 \ln (-\psi m), \qquad (11)$$

where a, b_1 and b_2, are the coefficients in the multiple regression, T is the soil temperature, $-\psi m$ is water potential and G is time to germination.

Emergence processes behave in a similar manner (Figs 10, 11). For example comparing the water content curves of 0.15 - 0.17 m^3/m^3 (Figures 10 and 11) in both soils, Carroll clay loam shows longer germination time in each temperature intersection point, because of a differential retentive capacity.

Influence of soil compaction and seeding depth on germination and emergence

Compaction causes a rearrangement of the soil particles and as a result many properties of the soil are influenced. Pore size distribution is altered, total porosity is decreased, and there are changes in the movement and content of heat, air, water and nutrients in the soil. The restricted growth of roots commonly observed in

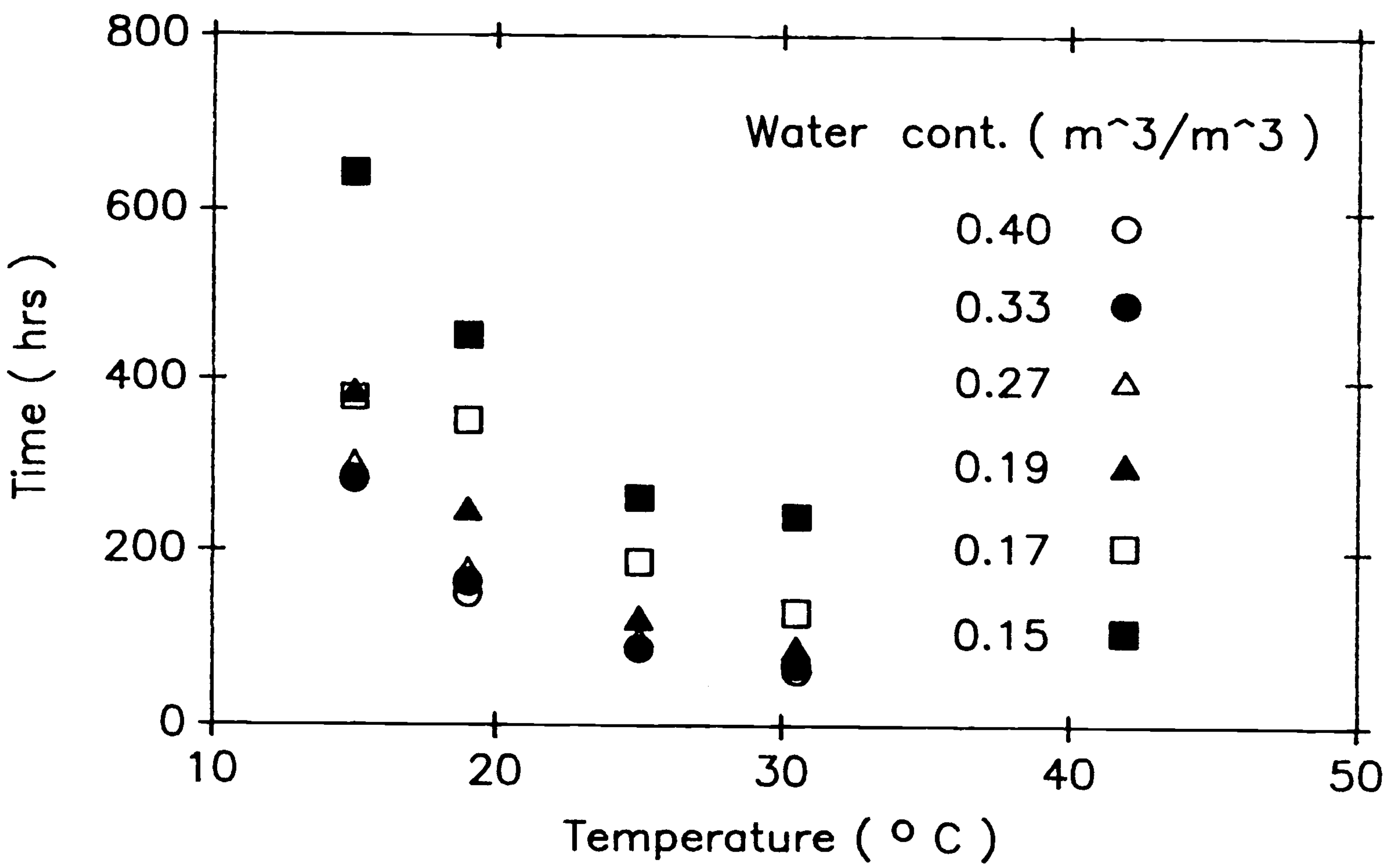

Figure 10: Effect of soil temperature at different soil water potentials on 50% emergence of corn Pioneer 3995 in a Carroll series clay loam (Cutforth, et al. 1985).

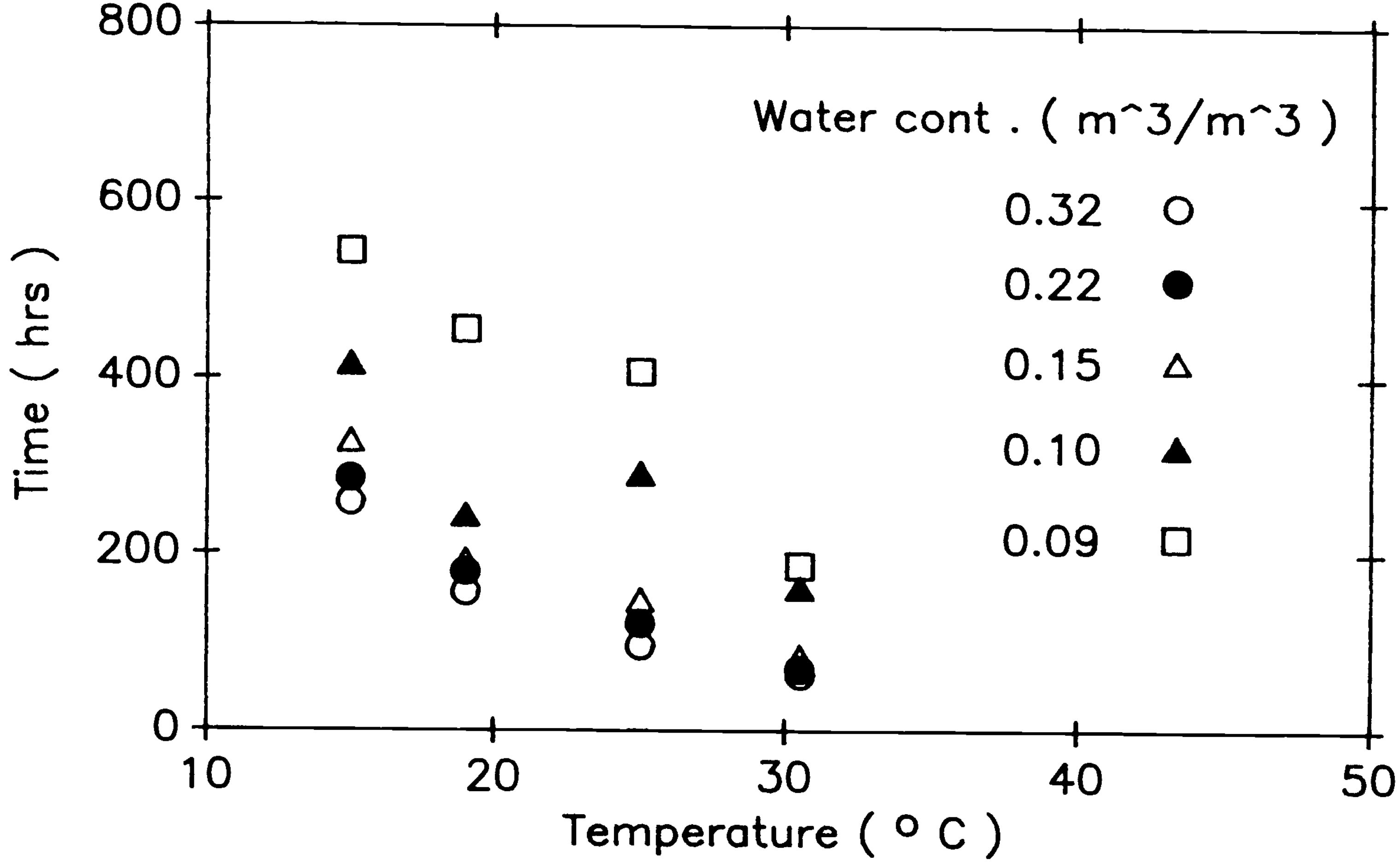

Figure 11: Time to 50% emergence of corn Pioneer 3995 as a function of temperature and volumetric water content from the data of Almasippi series loamy sand (Cutforth, et al. 1985).

compacted soil has been variously attributed to all of these properties, and to the high mechanical resistance that compacted soil presents to plant roots (Hillel, 1982).

Hanks and Thorp (1956), studied the relationships between seedling emergence of wheat, bulk density, oxygen diffusion rate, and crust strength in three different textures: silty clay, silt loam and very fine sandy loam. They used different soil water contents from field capacity to 1/4 available water remaining in the soil at various bulk densities from 1.1 Mg/m^3 to 1.6 Mg/m^3.

The results indicate that for a constant bulk density, the lower the moisture content, the slower the seedling emergence rate.

Figure 12 shows the relationship between percent seedling emergence and time required for emergence at different bulk densities for three soil textures studied. Measured also at field capacity moisture content, seedling emergence was not limited for the Munjor silty clay loam soil until bulk density was 1.2 - 1.3 Mg/m^3, whereas for Keith silt loam soil limitation occurred at 1.3 - 1.4 Mg/m^3. For Albion fine sandy loam the limiting bulk density was 1.5 -1.6 Mg/m^3. Increase in particle size distribution as well as bulk density, and consequently changes in air pore space and a greater soil strength are responsible for the restriction of seedling emergence.

In this experiment, the oxygen diffusion rate was also measured. As soil compaction was increased from optimum, depending on soil, the oxygen diffusion rate decreased. Consequently, Figure 13 shows that when the oxygen diffusion rate decreased, seedling emergence was lower. Therefore, choosing 80% seedling emergence as a satisfactory

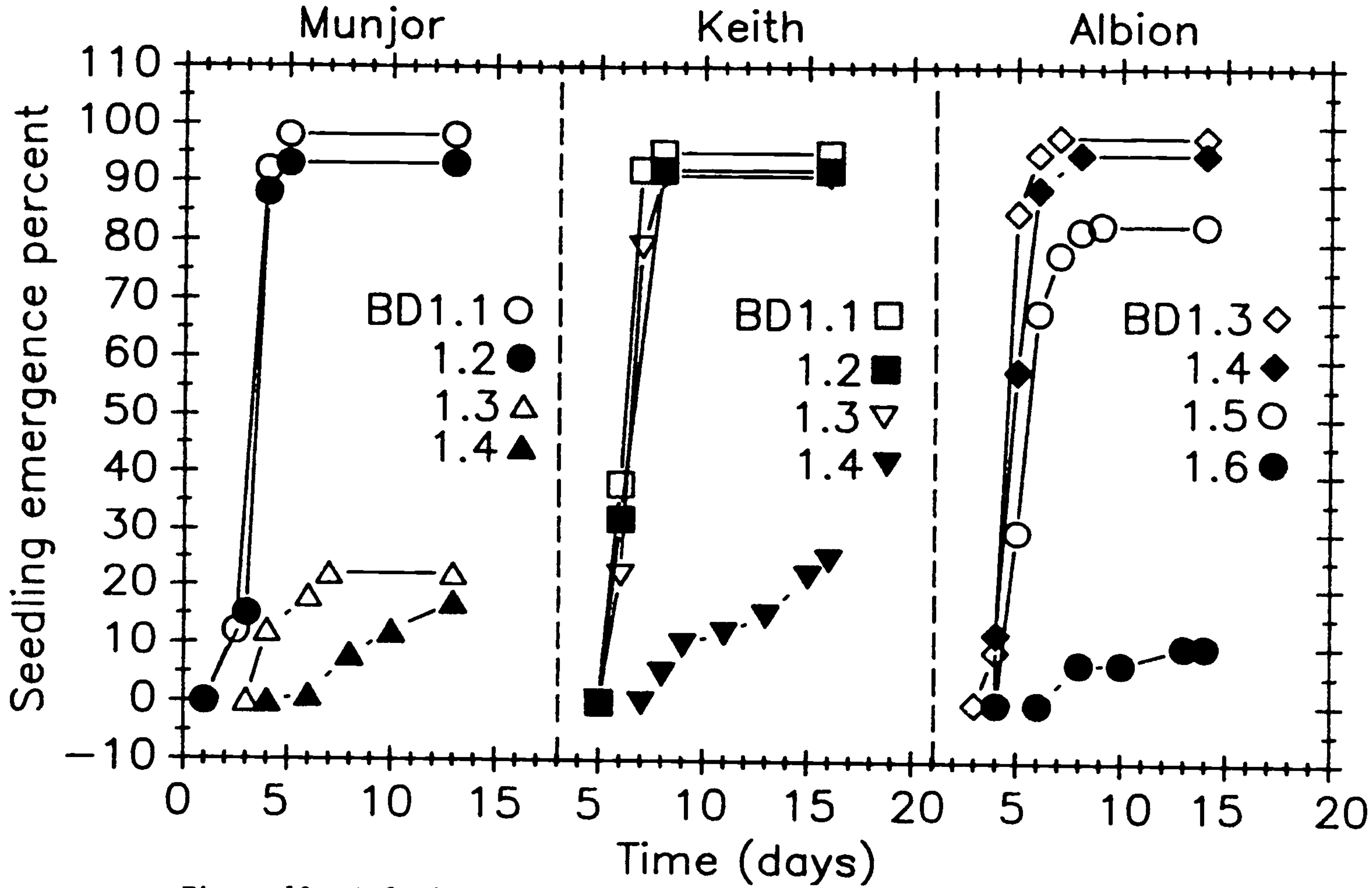

Figure 12: Relationship between percent of seedling emergence to time to emerge at various bulk densities and at field capacity for three different textures: Munjor - silty clay loam, Keith - silt loam and Albion - fine sandy loam. Temperature is not given. BD - bulk density in Mg/m^3 (Hanks and Thorp, 1956).

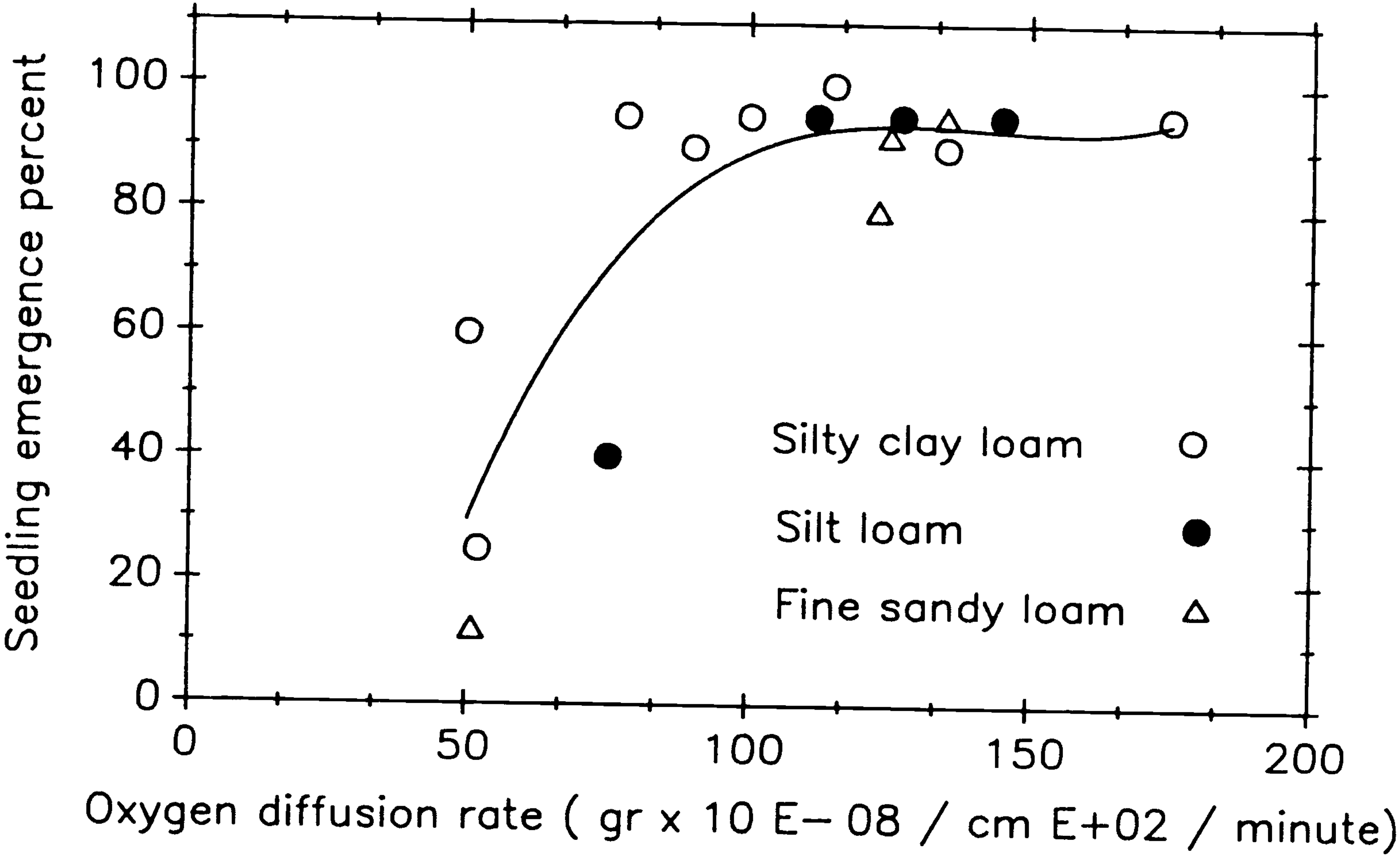

Figure 13: Relationship between percent seedling emergence oxygen diffusion rate at three soil textures. Temperature is not given (Hanks and Thorp, 1956).

criterion for all soils, this data also show that oxygen diffusion rate must be in the range of (75 to 100) x 10^{-8} gr/cm^2/min, corresponding to an air pore space of 15% in the silty clay loam, 17% in the silt loam and 25% in the fine sandy loam.

In another experiment, Lindstrom et al (1975), used different seeding depths of wheat (3, 9, and 12 cm) varying the temperature and soil water potential. In this experiment, emergence times were calculated using formulas and compared to measured values for 15 and 25°C. Figure 14 shows that at 25°C, seedlings of 3 cm depth had the shortest emergence times compared to 9 and 12 cm. After -7 bars of water potential, emergence time for this depth increased exponentially.

In this study wheat germination rate progressively decreased as water potential decreased. However, the authors pointed out that they never obtained complete emergence (80%) below a water potential of -10 bars.

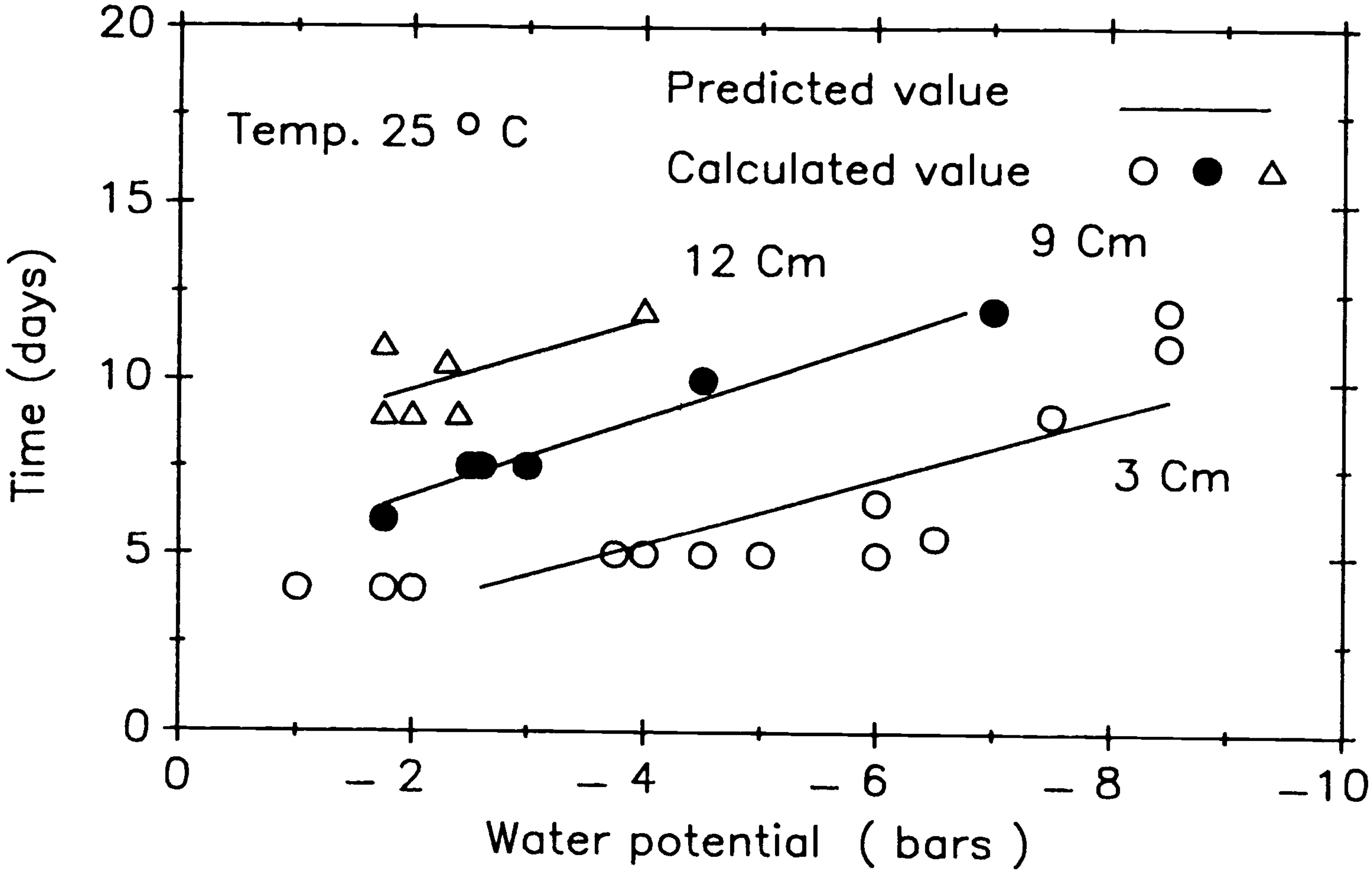

Figure 14: Emergence time as a function of soil water potential for three depths of planting at 25°C, comparing predicted and calculated values (Lindstrom, et al. 1975).

III. METHODS AND MATERIALS

In order to determine how the maize seeds react to different soil-water potentials, temperatures, bulk densities and seeding depth, seeds were exposed to different treatments. Only one hybrid of corn was selected and one kind of soil was used. The seeds were a hybrid of Funk (DJ7 x LH93). The relative maturity was 113 days (Minnesota) with a high water stress resistance.

Three experiments were carried out:

1) The first pertained to the germination process. The objective was to know the range of influence of the main variables and optimum temperature and water potential interaction.
2) The second pertained to the emergence process. The objective was to study the relationship among all variables introduced: soil temperature, soil water potential, bulk density and seeding depth.
3) The third pertained to compaction and used a level of soil water potential of 100 kPa and 20°C of soil temperature. The purpose was to determine when compaction begins to be a limitation in this condition.

Germination

This experiment was carried out using solutions of different water potentials prepared by mixing polyethylene glycol and distilled water. Matric potentials of -33, -100, -500 and -1000 kPa were created by the osmotic solutions of polyethylene glycol with a molecular weight 8000 (Carbowax 8000).

Water potential of solutions of polyethylene glycol vary linearly with temperature and quadratically with concentration. This relation is described by the equation proposed by Michel (1983) and Michel and Kaufmann (1973).

$$\psi = 1.29\ [\mathrm{PEG}]^2\ T - 140\ [\mathrm{PEG}]^2 - 4.0\ [\mathrm{PEG}], \qquad (12)$$

where ψ is water potential in bars, PEG is concentration of polyethylene glycol in gr/cm^3 water, and T is temperature in °C. This equation was used to calculate needed concentrations. Concentrations were converted to gr PEG/cm^3 H_2O based on displacement of 0.84 cm^3 H_2O/gr PEG and a water density of 0.997 g/cm^3 at 25°C (Michel, 1983).

To simplify calculation of polyethylene glycol concentration required for particular water potential and temperatures, equation 12 was rearranged:

$$[\mathrm{PEG}] = \frac{(4 - (5.16\ \psi\ T - 560\ \psi + 16)^{0.5})}{(2.58\ T - 280)} \qquad (13)$$

The PEG was weighted with an analytical balance in petri dishes. The material was transferred to volumetric flask of 1000 ml using funnels and a squeeze bottle. The PEG was dialyzed to remove any possible impurities that might have a toxic effect on germination (Sharma, 1976).

To inhibit microbial growth in the PEG solutions, 1 ml of formaldehyde was added to each liter of solution (Waldron and Manbeian, 1970).

Each solution was stored separately and then checked with a vapor pressure osmometer (Wescor 5100 C).

The osmometer consists of a thermocouple junction of chromel and constantan wire in a small closed chamber. This device has a microvoltmeter which measures the electrical flux. When a current passes in a special direction, heat is carried off in direct relation to the amount of current (Peltier effect).

The osmometer was calibrated using a small piece of filter paper placed in the chamber and using standard solutions of 100, 290, 1000 mM/kg of NaCl in water.

By first cooling the thermocouple junction electrically for a short period of time water vapor was condensed onto a junction with potential = 0. When the cooling was stopped the water on the junction evaporated and condensed on the sample solution which had a negative potential. Since the temperature depression of the thermocouple junction was proportional to the rate of evaporation from the junction, measuring the temperature depression with the microvoltmeter gave to get the total molar concentrations of the samples. Calculations were done using the following formula:

$$\Pi = M\ R\ T, \tag{14}$$

where Π is the osmotic pressure in atmospheres, M is total molar concentration, T is temperature in °K, and R is the gas constant

(0.08205 liter atm/deg.mole).

Pieces of blotter paper exactly 27x21 centimeters were saturated with the osmotic solutions and placed in shallow metallic trays of 22 x 22 x 5 centimeters. Sixteen corn seeds were scattered on the blotter paper in each tray and separated approximately 4 centimeters between seeds and 7 centimeters from the border of the sheet. Finally, to prevent evaporation losses, a plastic cover was placed over each tray (Halitligil, 1975).

The seeds were treated previously with the fungicide Thiram (Arasan) in doses of 4 pound of active product per gallon of treatment to eliminate fungal effects.

The experiments were carried out in the dark by placing the trays in an environmental growth chamber with 1.4 m^3 of growing area with controllable temperature range and humidity. For higher temperatures a Napco model 620 oven was used.

Water potential treatments were -33, -100, -500 and -1000 kPa. Temperature treatments were 20, 25, 30, and 35°C.

Both the rate and cumulative germinations were recorded every 12 hrs by identifying and removing germinated seeds using a forceps (Sharma, 1973). At the same time this operation allowed aeration of the airspace of the tray (Cutforth et al 1985).

The seeds were considered germinated when the length of the protruding radicle reached 2 mm or more (Collis-George, 1966; Heydecker, 1972; Sharma, 1973; Hadas and Russo, 1974).

Time between two germination observations was estimated as a function of radicle length.

Statistical design

A randomized block design with a split-plot arrangement and three replications was used. Temperature was the large plot and water potential the sub-plot. Temperature was assigned at random to strips of trays within each of three blocks.

Levels of factor A (temperature): 20, 25, 30, 35 °C.

Levels of factor B (water potential): -33, -100, -500, -1000 kPa.

Emergence experiment

This experiment was carried out on samples of the Camas sandy loam soil series, sandy-skeletal, mixed Fluventic Haploxerolls. This particular soil is described as deep, excessively drained, formed in recent sandy and gravelly alluvium and derived from various kinds of rocks. The pH was 6.1 and the particle size distribution was : sand 56.8%, silt 31,7% and clay 11.5%. The electrical conductivity was 0.6 ds.m.-1 and the bulk density was 1.3 Mg/m^3.

The soil was treated to eliminate any fungi or spores present, by exposure to temperatures above 60 - 70°C for 1 - 2 hrs in layers about one centimeter thick (Sharma, 1973). The soil was then passed through a 2.00 mm screen in order to reach uniformity.

The first step was to obtain the moisture retention curve of the soil using pressure plate and pressure membrane apparatus (Figure 15). From this curve the water content at soil matric potentials of -33, -100, -500 and -1000 kPa was calculated. Enough moist soil was prepared, and left to equilibrate for 10 days at room temperature in containers of 20 liters capacity. Checking by gravimetric

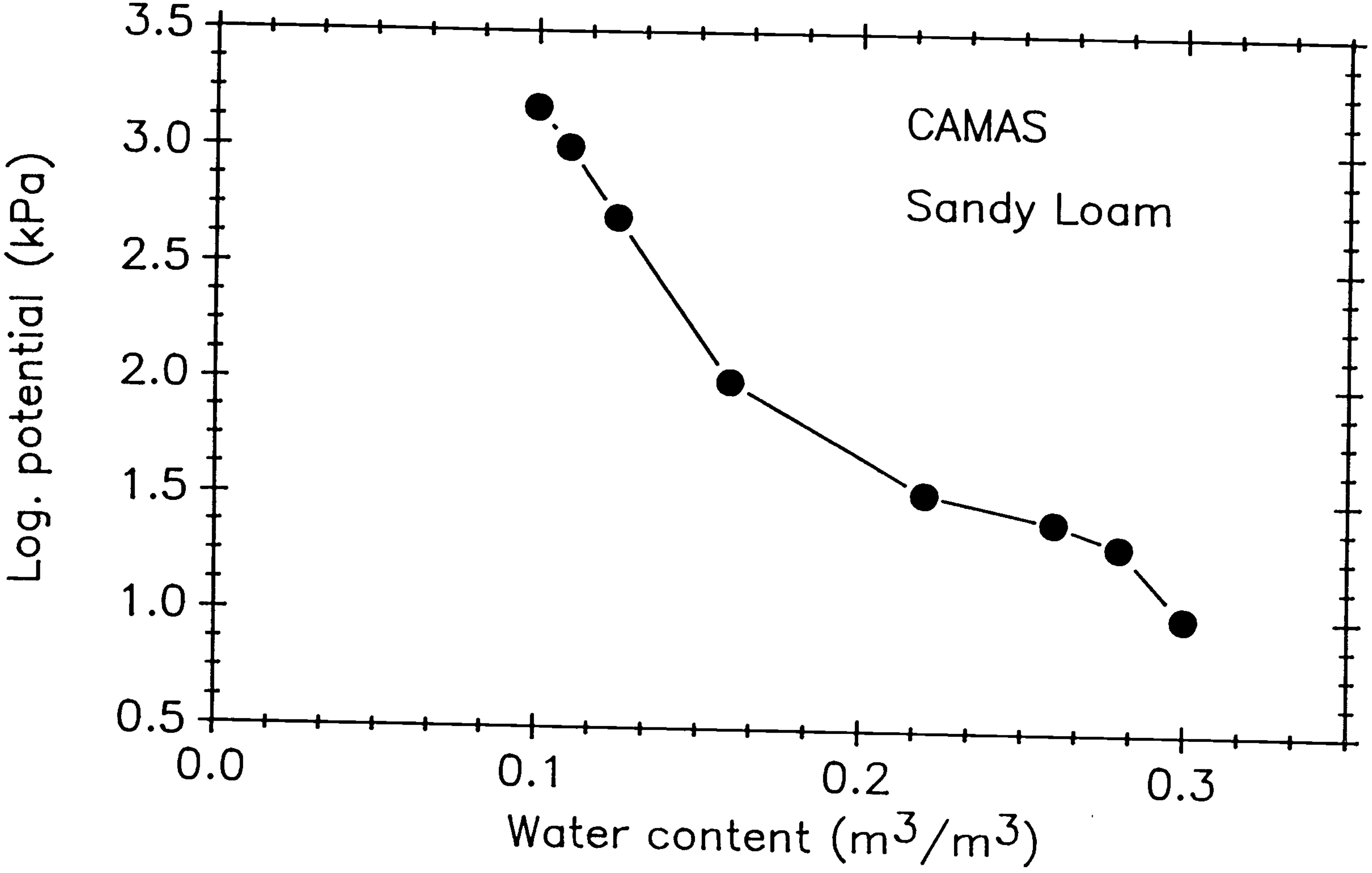

Figure 15: Water release curve for Camas sandy loam series

determination was done periodically. Small quantities of water were added if necessary and left to equilibrium for additional six days until the variation of water content was within 3.0%. Plastic covers were used in order to prevent evaporation losses.

In each temperature treatment, moist soil at corresponding soil water potential was placed in a 400 milliliter beaker to a volume of 300 milliliters. Ten corn seeds were placed at the desired seeding depth in a random manner. In some treatments, the soil was compacted before and after the seeding. Therefore, the corresponding ten corn seeds of uniform size were placed randomly on the surface of the leveled soil with the plumules facing upward (Schneider and Gupta, 1985), and covered with soil to complete the desired volume. Bulk density treatments were: no compaction (1.29 Mg/m3) and compaction (1.36 Mg/m^3) and seeding depth treatments were 3 and 7 cm. Compaction was done by compressing the soil with a constant weight (0.118 kg/cm^2), similar to the force applied by a pressing wheel or packing wheel of a driller, equivalent to 4 kg over 36 cm^2 which was the total area of the beaker (Christensen, 1988).

The beakers were covered with plastic held in place by rubber rings to prevent evaporation losses.

The beakers were placed in the same growth chamber and oven used for the germination experiment. The location of the beakers within the growth chamber were rearranged twice daily to minimize the influence of spatial variability (Schneider and Gupta, 1985). Each temperature treatment was run separately.

Temperature treatments were 20, 25, 30, and 35°C. Emergence was monitored at least twice a day up to appearance of 80% of coleoptiles. A temperature recorder provided a continuous record of air temperature within the growth chamber.

After 80% emergence or after a maximum of 25 days, the beakers were removed from the growth chamber, the water content was rechecked by oven drying, and the soil was discarded. Tests showed small (5-10%) moisture loss during a trial.

Statistical design

Statistical design was a split-split-plot design. Temperature was considered the whole plot and soil water potential, bulk density and seeding depth were considered the subplots. Three replications were performed. Variables introduced were:

a) Temperature: 20, 25, 30, 35°C.
b) Soil water potential: -33, -100, -500, -1000 kPa.
c) Seeding depth: 3 and 7 cm.
d) Bulk density: no compaction (1.29 Mg/m^3) and compaction (1.36 Mg/m^3).

Soil compaction experiment

A sufficient amount of soil previously sterilized was screened to pass through a 2 mm screen. Water was added to bring it to -100 kPa of soil water potential. The soil was stored for 6 days and then thoroughly mixed to obtain a uniform mixture of soil and water. Soil water content was checked gravimetrically until the variation in soil water content was 3%.

Soil was placed in the beakers to give a 3 centimeter layer when compacted. Ten corn seeds were scattered on the soil surface and then covered with soil to a volume of 300 cm^3. The top layer was similarly compacted. Compaction was accomplished by means of a flat rubber plate, slightly smaller than the beaker and loaded with a static load (Hillel, 1982), which was placed on the top of the soil.

Varying the static load from 0.1171 kg/cm^2 to 0.7812 kg/cm^2 in four treatments, the soil physical condition of the seedbed was changed. This technique permitted a more uniform distribution of density and prevented a packing interface between the successive layers. Bulk density was calculated for each replication.

The beakers were covered with plastic and sealed to prevent loss of water through evaporation and were placed in a growth chamber at 20°C of, in darkness. Seedling emergence was monitored each 12 hours until 80 percent of the coleptiles had emerged.

Statistical design

A completely randomized design was used with four treatments and four replications: 4.250, 12.250, 20.250, and 28.250 kg of static load equivalent to 0.1171, 0.3375, 0.5580 and 0.7812 kg/cm^2 respectively.

The variable to be measured was the effect of compaction of the seedbed as a consequence of static load on corn emergence.

IV. RESULTS AND DISCUSSION

Germination

Water potential influence

The data show that decreased osmotic potential levels progressively delayed germination (Table 1). Water availability was the main cause for this phenomenon because it determined the uptake of water by the seed.

The driving force for movement of water by mass flow and diffusion from pore spaces in the interstices of soil into the tissues of the seeds is the difference in water potential at the two ends of the pathway. The flux is controlled by diffusivity, which in a porous medium is a function of the water potential.

Water uptake begins with the process of imbibition which is a physical process related to the properties of the colloids. By this mechanism molecules of water enter the seeds, causing solvation of the colloid particles which then swell and occupy the free capillary spaces. During imbibition water uptake occurs through the pericarp. The seed swells rapidly and the embryo is the first tissue to resume DNA synthesis activating the primary root. The main component which imbibes water is the protein (Douglas and Paleg, 1981).

As the concentration of polyethylene glycol increased, the process of imbibition and radicle protrusion was delayed. Below -500 kPa, time to germination increased exponentially. The increase was steeper at low temperature (20°C). All these sharp increases in time are presumably related to the approaching critical or threshold water

Table 1: Time in hours to attain 80% of germination as a function of temperature and water potential. Results averaged over blocks.

Temperature	Osmotic Potential (kPa)			
	-33	-100	-500	-1000
°C	Hours			
20	89.0	90.6	129.3	241.6
25	64.0	71.0	78.6	173.6
30	55.3	60.0	77.6	157.0
35	57.3	66.0	80.6	218.0

potential for germination, an abrupt cut-off or lower limit that varies with plant species.

Temperature influence

The number of hours to reach 80% of germination decreased as temperature increased until the optimum was reached (Table 1).

Optimum germination time was at 30°C, increasing above and below this temperature. This increment was more important at the lowest water potential of -1000 kPa. At high potential the time of germination decreased slightly until the optimum temperature.

As temperatures were increased above the optimum level, from 30°C to 35°C, the germination time which was initially lower, increased to a higher level. This increase was ascribed to a time-dependent thermal denaturation or progressive change in configuration of the enzymes and proteins. Supraoptimal temperatures reduced the capacity of the seeds to germinate in the darkness by thermal inactivation of preexisting active phytochrome.

As temperature rises, physiological processes are speeded until the seed is unable to synchronize its biochemical processes correctly and dies. The metabolic imbalance becomes so severe that the rate of germination is reduced, showing a progressive decline (Heydecker, 1972).

Temperature-water potential effect

Lowering either temperature or water potential significantly delayed germination, but lowering both resulted in a greater delay.

When the temperature was 30°C (Table 1), lowering osmotic potential from -100 kPa to -1000 kPa increased germination time from 60 hrs to 157 hrs or 97 hrs. However, when the temperature was 20°C, lowering the water potential from -100 kPa to -1000 kPa time increased germination time from 90.6 to 241.6 hrs or 151 hrs.

The influence of water potential was more important at colder temperatures than at warmer temperatures.

On the other hand, when the osmotic potential was held at -100 kPa, lowering the temperature from 30°C to 20°C, time of germination increased from 60.0 to 90.6 or 30.6 hrs. However, when osmotic potential was held at -1000 kPa, germination time increased from 157 to 241.6 hrs or 84.6 hrs.

Considering the same temperatures 30°C and 20°C, but instead a decrease in potential to -1000 kPa, the treatment of -500 kPa, the results were as follow: when the temperature was held at 30°C, the change from -100 kPa to -500 kPa was from 60 hrs to 77.6 hrs or 17.6 hrs difference.

Lowering temperature from 30°C to 20°C, the difference between -100 kPa and -500 kPa was 39 hrs. When osmotic potential was held at -100 and -500 kPa, the difference in temperatures (30-20°C) were 30.6 hrs and 51.7 hrs respectively.

These last values (30.6 and 51.7 hours) were higher than 17.6 and 39 hrs (differences in time for changing water potential from -100 to -500 kPa). The differences between 30°C and 20°C (30.6 and 84.6 hrs), were lower than 151 and 97 hours (differences in time from -100 kPa to -1000 kPa).

From this analysis it is possible to see that changes in temperature from 30°C to 20°C were more important than changes in water potential from -100 to -500 kPa. This relationship was reversed at water potentials less than -500 kPa, where changes to -1000 kPa influenced germination time more than did soil water potential up to -500 kPa. Imbibition depends on temperature and proceeds more rapidly at higher temperatures. The viscosity of water decreases with increased temperature and its kinetic energy increases (Ehrler and Gardner, 1971).

Analyzing the total stress, it is possible to appreciate that for extreme temperatures, in this experiment 20 and 35°C, the increase in germination time below potentials of -500 kPa was different (Table 1). Although a cold environment generally constitutes a stress condition, lowering the temperature increases solubility of oxygen in water (Kozlowski, 1972). In addition, respiration of seeds decreases at lower temperatures, decreasing the rate of oxygen consumption. The result is that in colder situations the supply of oxygen might be more adequate for the seed than in warmer environments.

Mathematical model

The results show that germination of corn can be described by a mathematical relationship involving temperature and water potential. Mathematical description of the germination process has been suggested by Blacklow (1972), Lindstrom (1975), and Schneider and Gupta (1985).

The objective of modeling corn germination was to define the mathematical relationship between temperature and water potential within the range covered by this experiment.

Using multiple regression procedure polynomial equations were evaluated. As function of highest Cp criterion, lowest MSE (mean square error) and highest R^2 (coefficient regression) a quadratic relationship was selected using the stepwise variable selection method (Table 2). The best fit was obtained with the mathematical expression:

$$E(y) = \beta o + \sum_{i=1}^{K} \beta i xi + \sum_{i=1}^{K} \beta ii\ xi^2, \tag{15}$$

where:

$E(y)$ = response (yi)

βo = intercept

βi = linear coefficient for the ith input

βii = the quadratic coefficient for the ith input

xi = the level of the ith input.

The polynomial equation for germination as a function of temperature and water potential is:

$$G = 554.070 - 34.389\ (T) - 3.838\ (P) + 0.586\ (T)^2 + 1.65\ (P)^2, \tag{16}$$

where:

G = time for germination in hours

T = temperature in °C

P = Osmotic Potential in kPa/-100.

Figure 16 shows the response surface developed using the polynomial function (equation 16). Figure 17 shows the relationship

Table 2: Coefficients for a model relating hours for germination as a function of temperature and water potential.

Independent variable	Coefficient	Std error	T-value	Significance level
Constant	554.1	102.9	5.4	0.0
Temp	-34.4	7.7	-4.5	0.0
Osmotic	-3.8	3.8	-1.0	0.3
Temp^2	0.6	0.13	4.2	0.0
Osmotic^2	1.6	0.36	4.5	0.0

$r^2 = 0.94$ SE = 13.96

Data over 16 observations set.

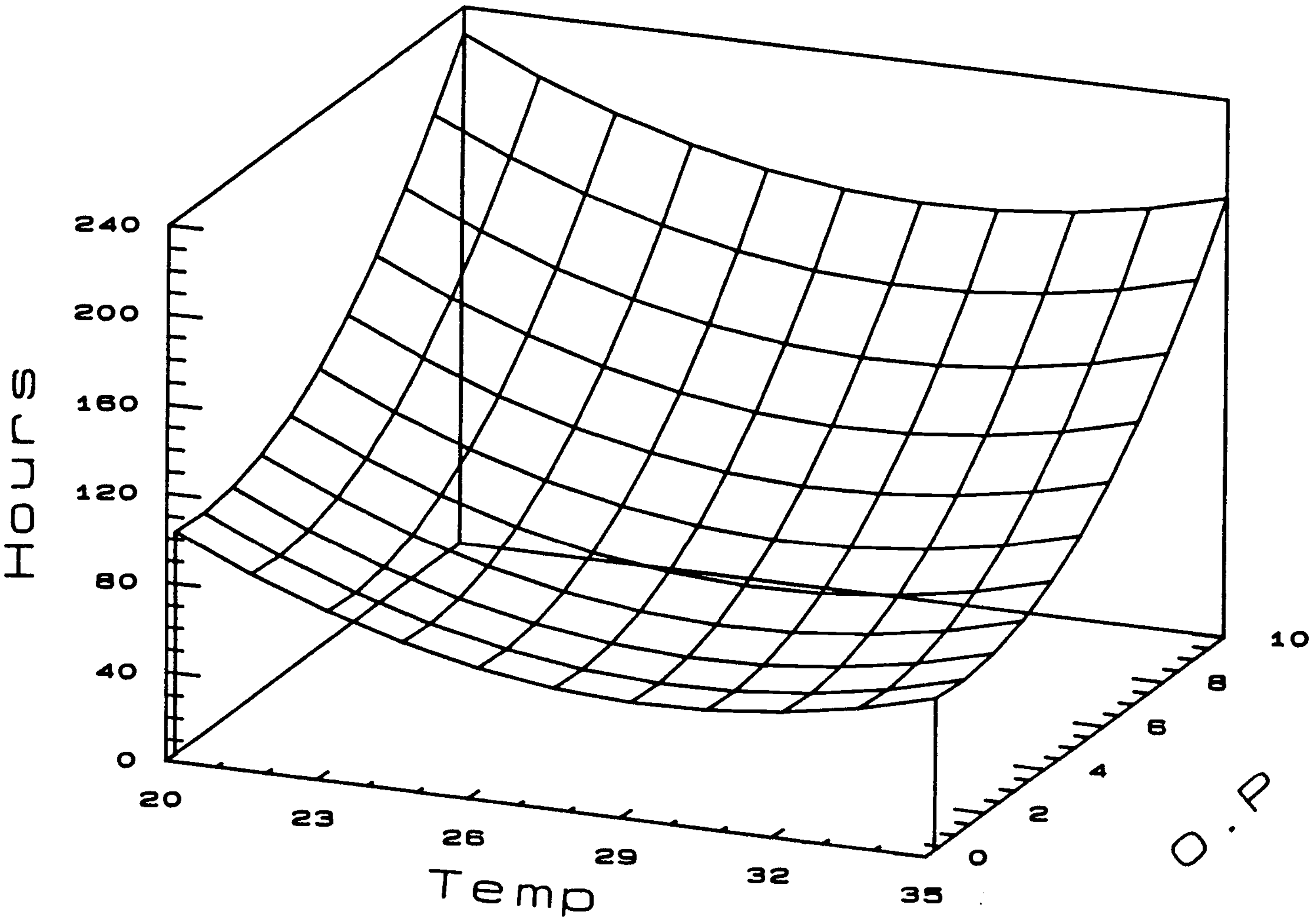

Figure 16: Polynomial response surface obtained with equation 16 showing germination time in hrs as a function of temperature in ^{o}C and water potential in kPa.

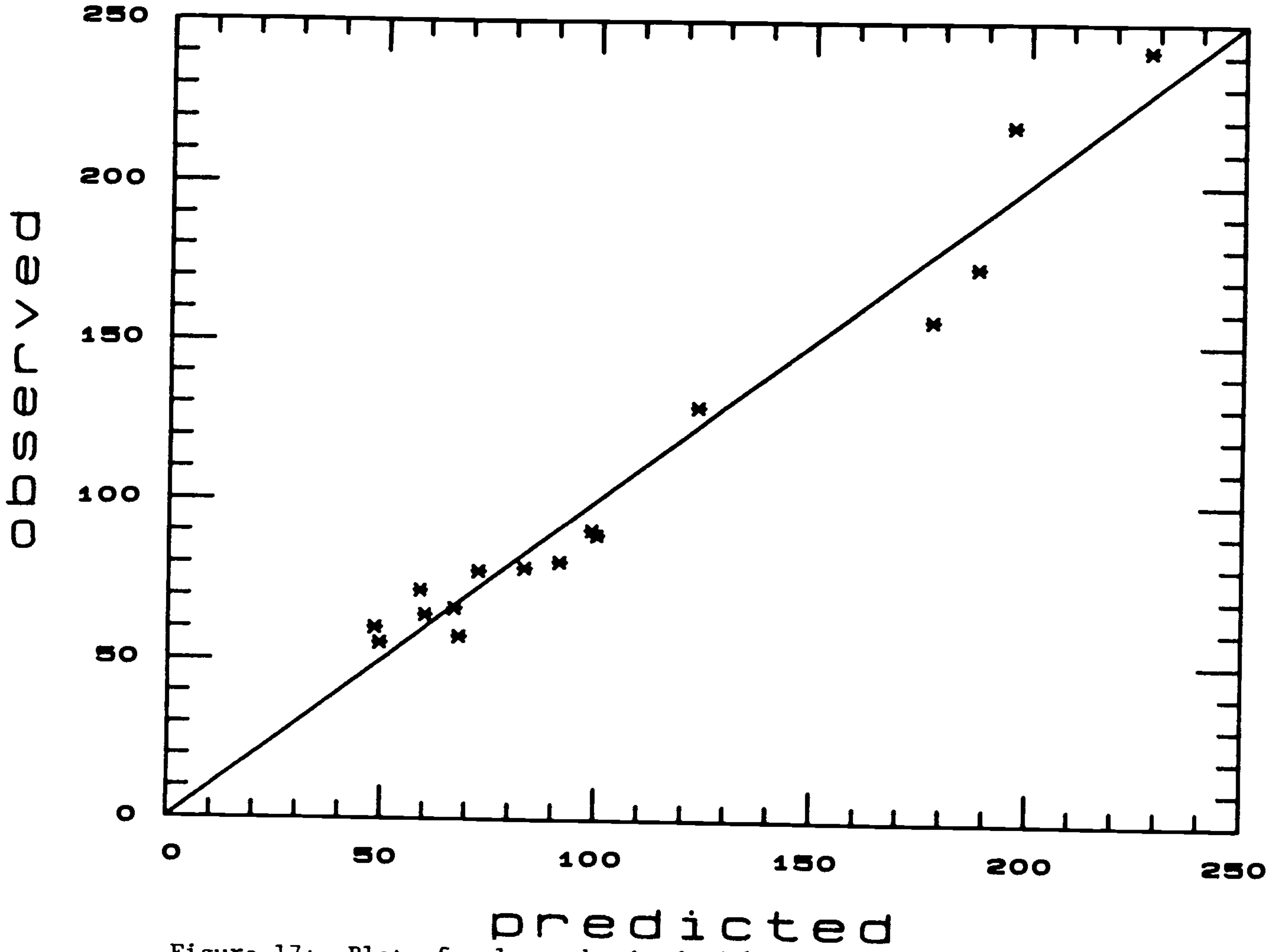

Figure 17: Plot of values obtained with equation 16 versus observed values for the dependent variable which is the time to obtain 80% germination.

between observed and predicted values with a 95% of confidence interval. The points are distributed uniformly about the diagonal line, suggesting that the model is a good representation of the experimental data.

Arrhenius analysis

The temperature coefficients (Q_{10}) of germination rates as described by Kotowski (1926), Forward (1960), and Hegarty (1973) were compared for the range 20-30°C using the formula:

$$Q_{10} = (K_2/K_1)^{10/T_2-T_1} , \qquad (17)$$

where K_2 and K_1 represent the germination rate at temperatures T_2 and T_1 respectively.

Using the equation stated by Arrhenius for chemical reactions, it was possible to calculate the energy of activation (E) or amount of energy that must be acquired by participating molecules before the reaction will proceed. The Arrhenius equation states :

$$d \ln K/dT = E/RT^2 \qquad (18)$$

which in the integrated form is:

$$\ln K = (-E/R) \ . \ (T^{-1}+C), \qquad (19)$$

where K is the germination rate in hrs, R the gas constant in kcal/deg.mole, T the absolute temperature, E the energy of activation kcal/mol and C the constant of integration.

Using the equation proposed by Forward (1960) and the data obtained with equation 16, values of E were calculated for a given temperature interval:

$$E = (4.6 \; . \; T_1 \; T_2/T_2 \; - \; T_1) \; . \; (\log K_2 \; - \; \log K_1) \qquad (20)$$

Results are shown in Table 3, Fig 18, and Fig 19. The Q_{10} values were higher at the colder temperature interval than at the warmer temperature interval. A similar situation was found for E, where highest values corresponded to the coldest temperature range. These graphs of Figs 18 and 19 also show that both Q_{10} and E, when plotted as a function of soil water potential using the calculated values from equation 16, show a decrease with decreasing water potential. The data point corresponding to -100 kPa had the highest value, however the difference with the result at -33 kPa was only small (Table 4, Fig 20).

The possible reason for the decreasing trend is that seed membranes are themselves the temperature sensors. Membranes change discontinuously with changes in temperature and simultaneously increase in leakiness.

According to Slayter (1967), three sites of resistance arise in a cell membrane: the membrane itself and the two interfaces between the solution and the membrane.

Numerous Van der Waals bonds give considerable stability to the

Table 3: Values of Q_{10} and E kcal/mol for different soil water potentials in the interval of 20-30°C of temperature.

SWP	Q_{10} (from eq.17)		E (from eq.20)	
	20-25°C	25-30°C	20-25°C	25-30°C
kPa			---------kcal/mol----------	
-33	2.8	1.5	16703.7	6496.6
-100	2.8	1.5	16990.7	6638.1
-500	2.2	1.3	12898.1	4558.1
-1000	1.5	1.1	6401.5	1863.6

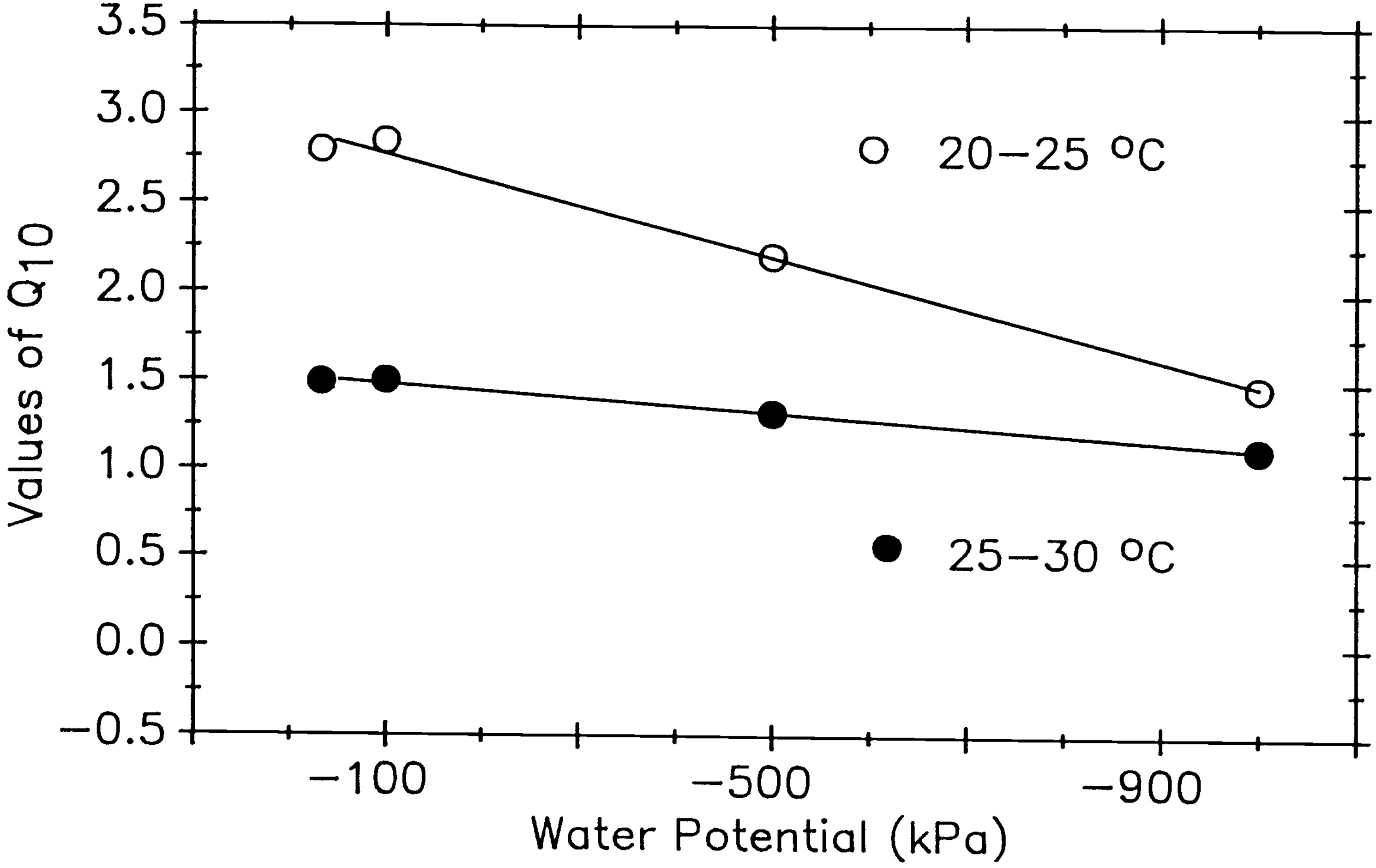

Figure 18: Values of Q10 as a function of soil water potential at two temperature intervals.

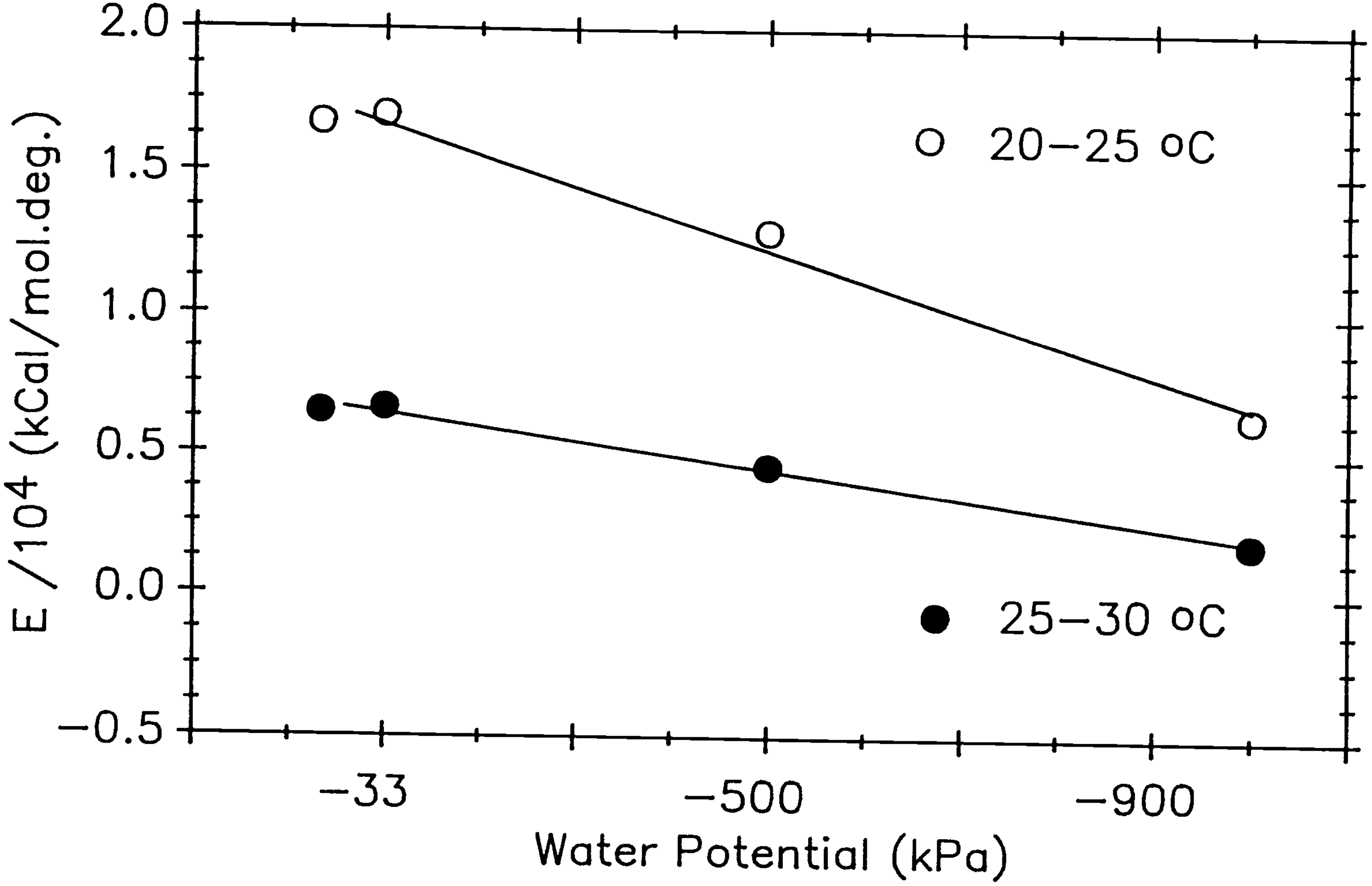

Figure 19: Activation energy as a function of soil water potential at two temperature intervals.

Table 4: Time in hours to attain 80% of germination obtained from the polynomial equation 16 and germination rates, which are 1/T.

Temp.	Soil water potential (kPa)							
	- 33		- 100		- 500		- 1000	
°C	Hours	1/Hrs	Hours	1/Hrs	Hours	1/Hrs	Hours	1/Hrs
20	99.6	0.01003	98.5	0.01015	122.7	0.00814	227.3	0.00439
25	59.5	0.01678	58.4	0.01712	82.6	0.01209	187.2	0.00535
30	48.7	0.02049	47.6	0.02100	71.8	0.01391	176.4	0.00566
35	67.3	0.01485	66.1	0.01512	90.3	0.01106	194.9	0.00513

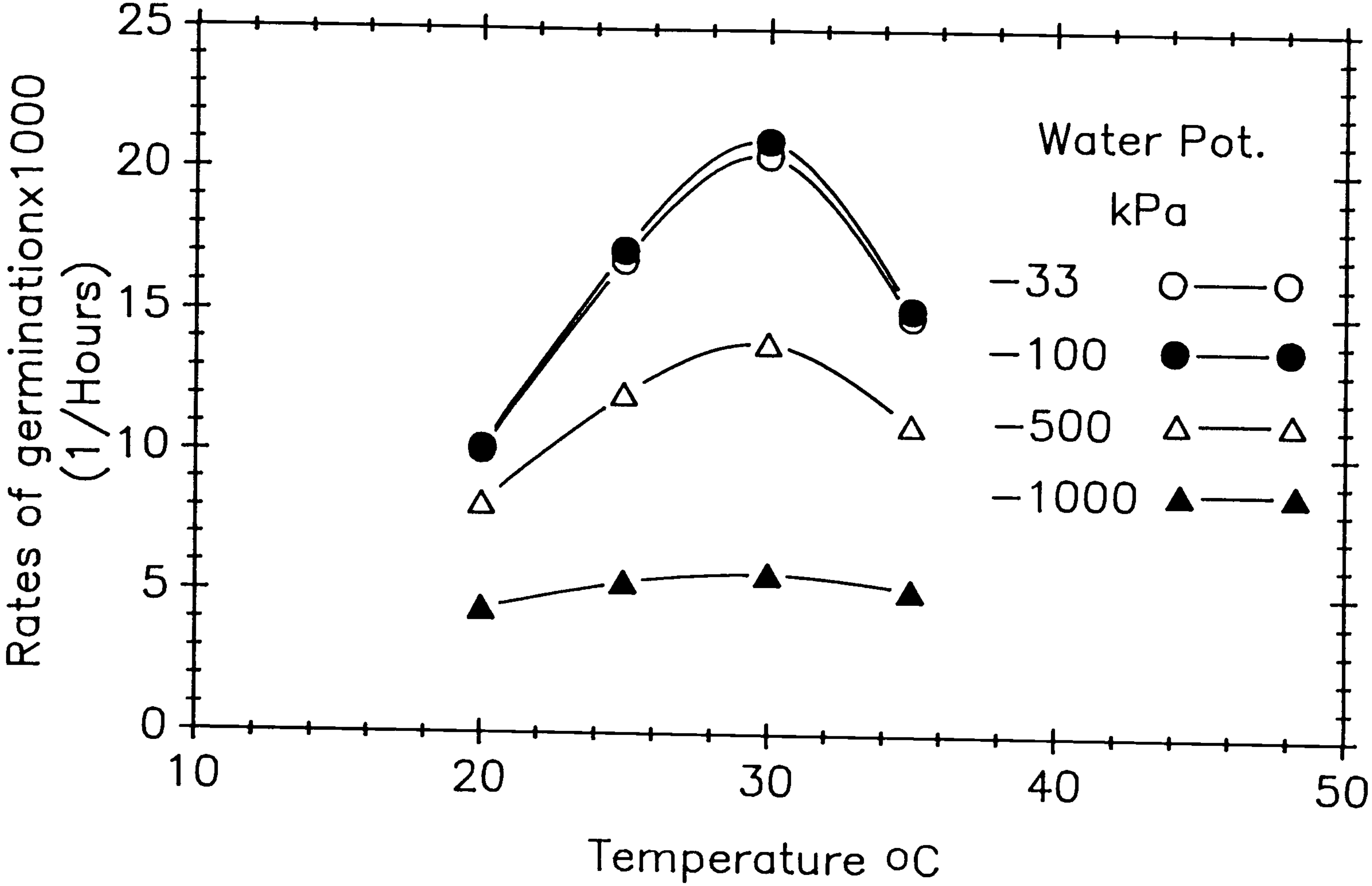

Figure 20: Germination rates (1/T) to attain 80% germination as a function of temperature and water potential.

neighboring lipid chains. In consequence, a water molecule passing through a membrane would encounter a variable resistance depending on the amount of existing forces. A minimum kinetic energy would be necessary to break that force and separate the lipid molecules. The amount of activation energy necessary quantifies the magnitude of the barrier to water movement and it is reflected in the Q_{10} of the water transport process.

Transient "pores" develop at low temperatures and probably single water molecules or transient files rather than continuous files account for most of the diffusing molecules.

Lower Q_{10} values correspond to low viscosity of water and consequently to a minimal resistance to water transport. Slayter (1967) also discusses that these low values, comparable to those observed with water transfer through physical systems, demonstrates that at high temperatures, membranes change from a high potential energy barrier to water transfer to one which is governed by the effect of viscosity. Changes in temperature not only directly affect the viscosity of the water, but also indirectly the protein configuration and elasticity of the membrane.

Speed of germination depends on the rate of chemical reactions that are responsible for the characteristic metabolism of each kind of germinating seed, in this case corn. In the interval 20-30°C enzyme-activated reactions existed, which showed an almost linear relationship between the logarithm of the rate of reaction and the reciprocal of the absolute temperature (the Arrhenius relationship) (Hegarty,1973).

In many enzyme-catalyzed reactions the logarithm of the rate of reaction plotted against the reciprocal of the absolute temperature yields a straight line suggesting that a single rate is involved in the germination responses to temperature.

Figure 21 shows that departures from linearity occurred. The breaks in all of the cases were produced near 25°C.

Over the first part of the range (30°C-25°C), the germination rate was less affected by temperature with higher rates and activation energy, than it was by the second part of the range (25°C-20°C), where the slope was higher, and lower rates together with higher activation energy values were obtained.

Statistical analysis

The model fitting results include the estimates of the model coefficients for each independent variable, the standard error of the coefficients, the t-value and the significance level for each t-value (Table 2).

The t-values represent the probability that a larger absolute t-value would occur if there were no marginal contribution from that variable. The t-statistics measure the marginal contribution of each variable as if it were the last to be entered into the model.

Variable osmotic showed a high level of significance of t-value (0.33) but the contribution to the fit at the time it entered the regression was important according to the F-value in Table 5.

Analysis of variance for the full regression was significant (Table 6), suggesting that all the variables in the model were

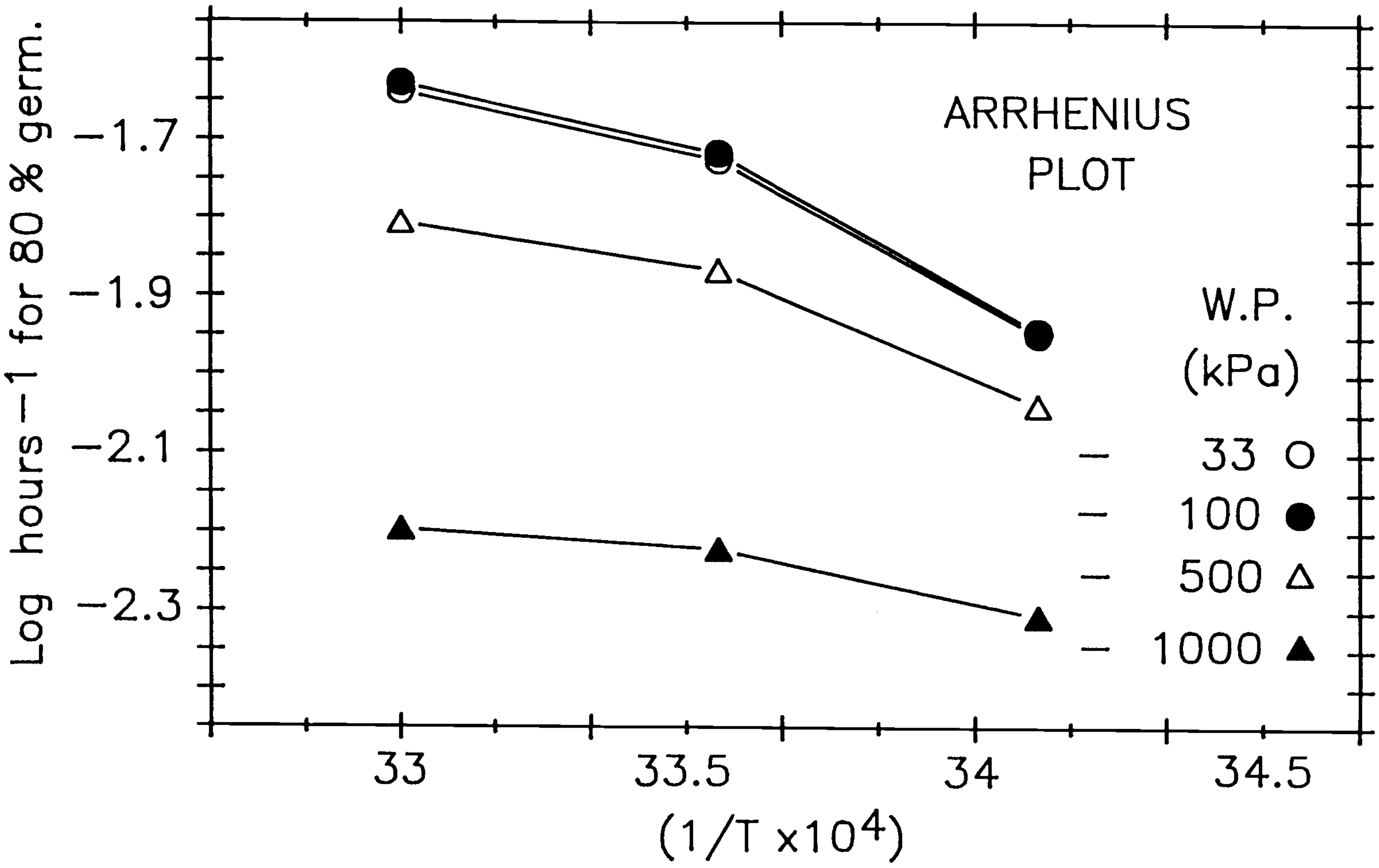

Figure 21: Logarithm of hours to attain 80% of germination as a function of inverse of absolute temperature.

Table 5: Further Anova for variables pertaining to use of equation 16.

Source	Sum of squares	df	Mean square	F-Ratio	P-value
Temp	2244.0	1	2244.0	11.5	.006
Osmotic	41093.1	1	41093.1	210.7	.000
Temp^2	3442.7	1	3442.7	17.6	.000
Osmotic^2	4042.2	1	4042.2	20.7	.000
Model	50822.0	4			

Table 6: Analysis of variance for the full regression.

Source	Sum of squares	df	Mean square	F-Ratio	P-value
Model	50822.1	4	12705.5	65.1	0
Error	2144.7	11	194.9		
Total (corr.)	52966.8	15			

R - squared = 0.95

R - squared (adj for d.f) = 0.94

Cp = 4.0

adequately fitted.

Analysis of variance for germination data using split-plot design (Table 7), showed highly significant ($P<0.01$) F-values for both interaction and main effects (FAB,FB, and FA). Blocking effect was not significant, but accuracy of the experiment was acceptable with 5.57% of coefficient of variation.

Table 7: Analysis of variance table for split-plot design in germination experiment.

Source	df	Sum of squares	Mean square	F value	
Rep	2	84.9	42.4	0.9	FR
Temp (A)	3	17152.9	5717.6	119.3	FA **
Error	6	287.4	47.9		
Osm.Pot(B)	3	135771.6	45257.2	1275.3	FB **
Int (A.B)	9	6104.7	678.3	19.1	FAB **
Error	24	851.6	35.4		

** highly significant

Coefficient of variation: 5.57%

SE for mean group 1 = 1.73 (16 obs) Σcases/n

SE for mean group 2 = 1.99 (12 obs) Σtemp/n

SE for mean group 4 = 1.71 (12 obs) ΣSWP/n

SE for mean group 6 = 3.43 (3 obs) ΣReps/n

Significance test:

F(AB) = 1275.35

FTAB(9,24) = 2.30 0.05% Since FAB >> FT(AB)

3.25 0.01%

Emergence

Emergence of corn was greatly influenced by soil water potential and soil temperature for both 3 and 7 cm seeding depth. Results showed that as temperature increased from 20°C to 35°C, time to emergence decreased until the optimum of 30°C, and then increased again (Tables 8 and 9).

When decreasing soil water potential from -33 to -1000 kPa, the time to emergence increased. Comparing the emergence data for the soil that was not compacted , it is noted that emergence occurred in some cases faster than germination, especially at -1000 kPa of soil water potential. The reason for that is presumably related to a different hydraulic conductivity in the soil system compared to the blotter paper-system as well as the different soil-water contact area (Williams and Shaykewich, 1971). Below -500 kPa, blotter paper-system was less stable than soil-system, and the major factor responsible for that difference in time between the two systems was the diminution of the hydraulic conductivity.

During imbibition the initial driving force for water movement between soil and seed was considerable and despite high resistance in the seed tissue, absorption in the first hours was rapid.

Germination culminates in radicle emergence without an increase in cell number, and the control of germination lies in the control of cell extension. In consequence, maintenance of turgor is an obvious requirement for cell expansion and in this phase it can be argued that germination can be controlled and promoted by decreasing water potential.

Table 8: Time in hours to attain 80% of total emergence, as a function of temperature (°C), water potential (kPa) and bulk density (Mg/m^3), when seeding depth was 3 cm.

Temperature	Compaction	Soil water potential (kPa)			
		-33	-100	-500	-1000
°C		Hours			
20	N C	115.3	127.6	206.6	192.6
	C	115.0	146.0	210.0	210.3
25	N C	80.0	94.3	127.3	161.0
	C	79.3	95.0	123.5	194.0
30	N C	50.0	55.6	89.3	136.0
	C	51.0	60.0	89.6	131.6
35	N C	61.6	68.3	108.6	141.0
	C	62.0	69.0	107.3	142.0

N C = No compaction

C = Compaction

Table 9: Time in hours to attain 80% of total emergence, as a function of soil temperature (°C), soil water potential (kPa) and bulk density (Mg/m^3), when seeding depth was 7 cm.

Temperature	Compaction	Soil water potential (kPa)			
		-33	-100	-500	-1000
°C		Hours			
20	N C	127.3	143.3	236.0	276.0
	C	127.6	151.3	208.0	248.0
25	N C	95.3	103.3	154.0	206.0
	C	95.6	103.6	166.0	214.0
30	N C	68.0	69.3	112.5	184.3
	C	64.6	86.6	114.3	175.0
35	N C	73.3	89.0	119.0	226.0
	C	73.0	88.6	105.6	218.0

N C = No compaction

C = Compaction

In the germination-emergence process of corn, where cell extension precedes cell division, after the protrusion begins a mitosis-controlled period, which although it depends on soil water potential, is much more dependent on speed of cell division. In consequence, differences in time after -500 kPa can be proportionally shortened in the emergence step (Harper and Benton, 1966).

There were no differences between compaction and no compaction for both treatments, 3 and 7 cm of seeding depth (Tables 8 and 9). Seed corn is a big seed with a large seed surface area and presumably increments in soil-seed contact area produced by compaction were not significant in shortening time to emergence.

The seeding depth effect was an important fact for time to emergence. As the depth increased from 3 cm to 7 cm, time to emergence increased between 20 and 30% (Table 10). That increment was higher at higher temperatures, because the differences between 3 and 7 cm were increasing slightly as the total amount of hours was decreasing.

Table 11 shows the average difference for two ranges of soil water potential: from -33 to -500 kPa and from -500 to -1000 kPa at different temperatures. Time to emergence clearly increased in the last one as temperature increased from 20°C to 35°C, and this phenomenon is related to the relationship between the viscosity of the water and the temperature previously discussed.

Comparing the average in the two ranges for 3 cm of seeding depth versus 7 cm of seeding depth, it is observed that higher times were obtained in the range from -500 to -1000 kPa, and these results were

Table 10: Time in hours to attain 80% of emergence in the interval 20-35°C of soil temperature for the two seeding of depths of 3 and 7 cm in soil that was no compacted.

		Soil water potential (kPa)				
Temp.	Seeding depth	-33	-100	-500	-1000	Average
°C	cm	Hours				
20	3	115.3	127.6	206.6	192.6	160.5
	7	127.3	143.3	236.0	276.0	195.6
	Differences	12.0	15.7	29.4	83.4	35.1
	% increment					21.8
25	3	80.0	94.3	127.3	161.0	115.6
	7	95.3	103.3	154.0	206.0	139.6
	Differences	15.3	9.0	26.7	45.0	24.0
	% increment					20.7
30	3	50.0	55.6	89.3	136.0	82.7
	7	68.0	69.3	112.5	184.5	108.5
	Differences	18.0	13.7	23.2	48.5	25.8
	% increment					31.2
35	3	61.6	68.3	108.6	141.0	94.8
	7	73.3	89.0	119.0	226.0	126.8
	Differences	11.7	20.7	10.4	85.0	31.9
	% increment					33.6

Table 11: Difference in hours to attain 80% of emergence of corn as a function of soil water potential in the interval 20-35°C of soil temperature and the two seeding depths of 3 and 7 cm in soil that was not compacted.

		Soil water potential (kPa)				Average difference	
Temp.	Seeding depth	-33	-100	-500	-1000		
°C	cm	Hours				from -33 to -500	from -500 to -1000
20	3	115.3	127.6	206.6	192.6	45.6	-14
	7	127.3	143.3	236.0	276.0	54.3	40
25	3	80.0	94.3	127.3	161.0	23.6	33.7
	7	95.3	103.3	154.0	206.0	29.3	52.0
30	3	50.0	55.6	89.3	136.0	19.6	46.7
	7	68.0	69.3	112.5	184.5	22.2	72.0
35	3	61.6	68.3	108.6	141.0	23.5	32.4
	7	73.3	89.0	119.0	226.0	22.8	107.0

presumably related to the interaction of soil water potential with seeding depth.

Mathematical model

A mathematical model can be used to describe the results for both seeding depths of 3 and 7 cm. The purpose of modeling corn emergence was to define the mathematical relationships involved, specifically the main variables temperature and soil water potential in connection to the seeding depth.

Using the step-wise variable selection procedure a quadratic relationship was selected. Therefore by multiple regression procedure polynomial equations were evaluated as was previously done in the germination experiment. The best fit was obtained with the mathematical expression (15), using different coefficients for emergence:

$$E_3 = 611.582 - 35.961\ (T) + 0.570\ (T^2) + 15.854\ (W) - 0.72\ (W^2) \qquad (21)$$

$$E_7 = 756.647 - 45.617\ (T) + 0.743\ (T^2) + 13.587\ (W), \qquad (22)$$

where E_3 and E_7 are time in hours to emergence, W is water potential in kPa/100 and T is temperature in °C. Figures 22, 23, 24, and 25 show the polynomial surface response and the relationship between calculated and observed values for the emergence process at two seeding depths.

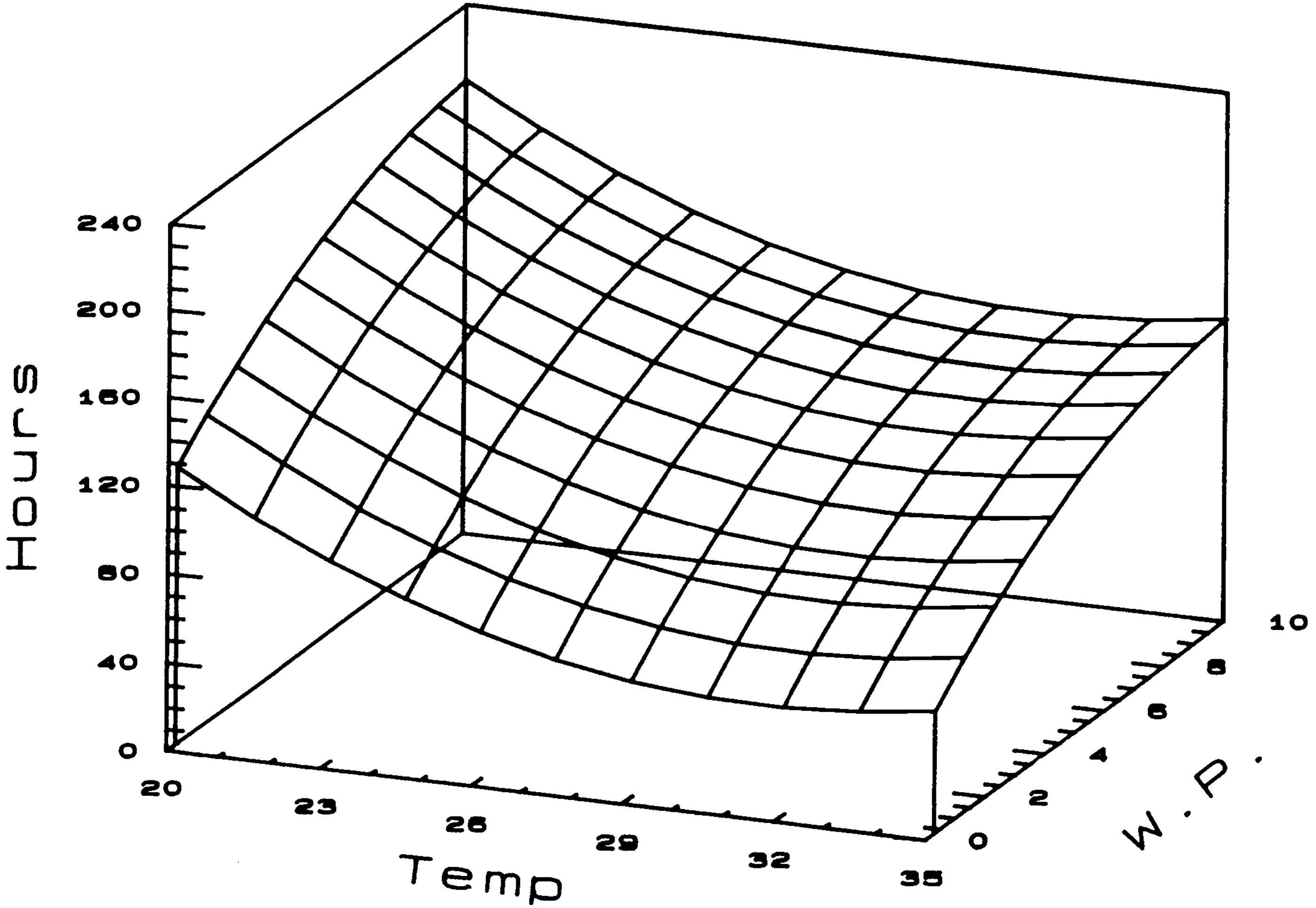

Figure 22: Polynomial response surface obtained with equation 21 showing emergence from 3cm of seeding depth as a function of temperature in ^{o}C and water potential in kPa.

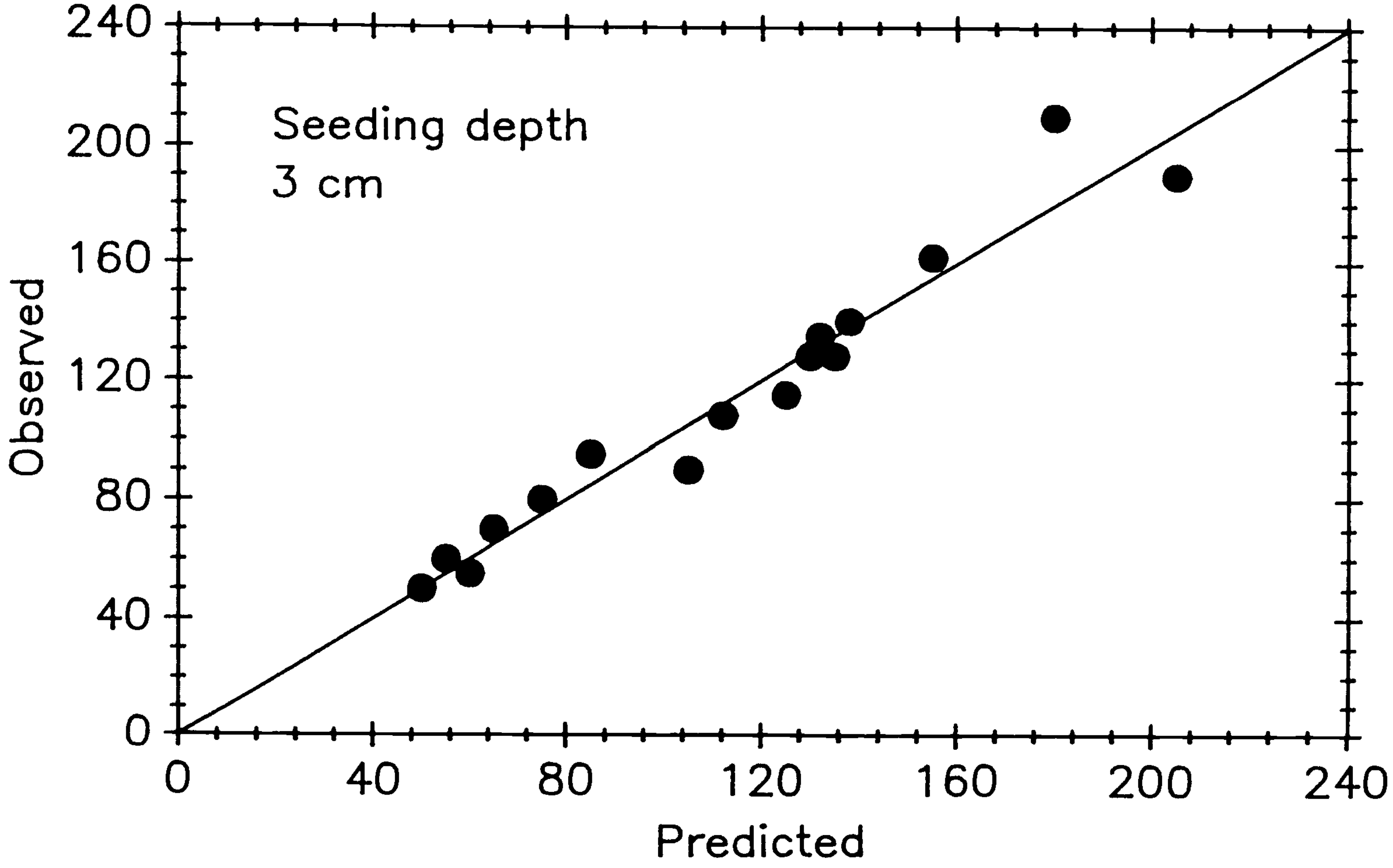

Figure 23: Plot of hours to obtain 80% emergence obtained with equation 21 versus observed values for the dependent variable.

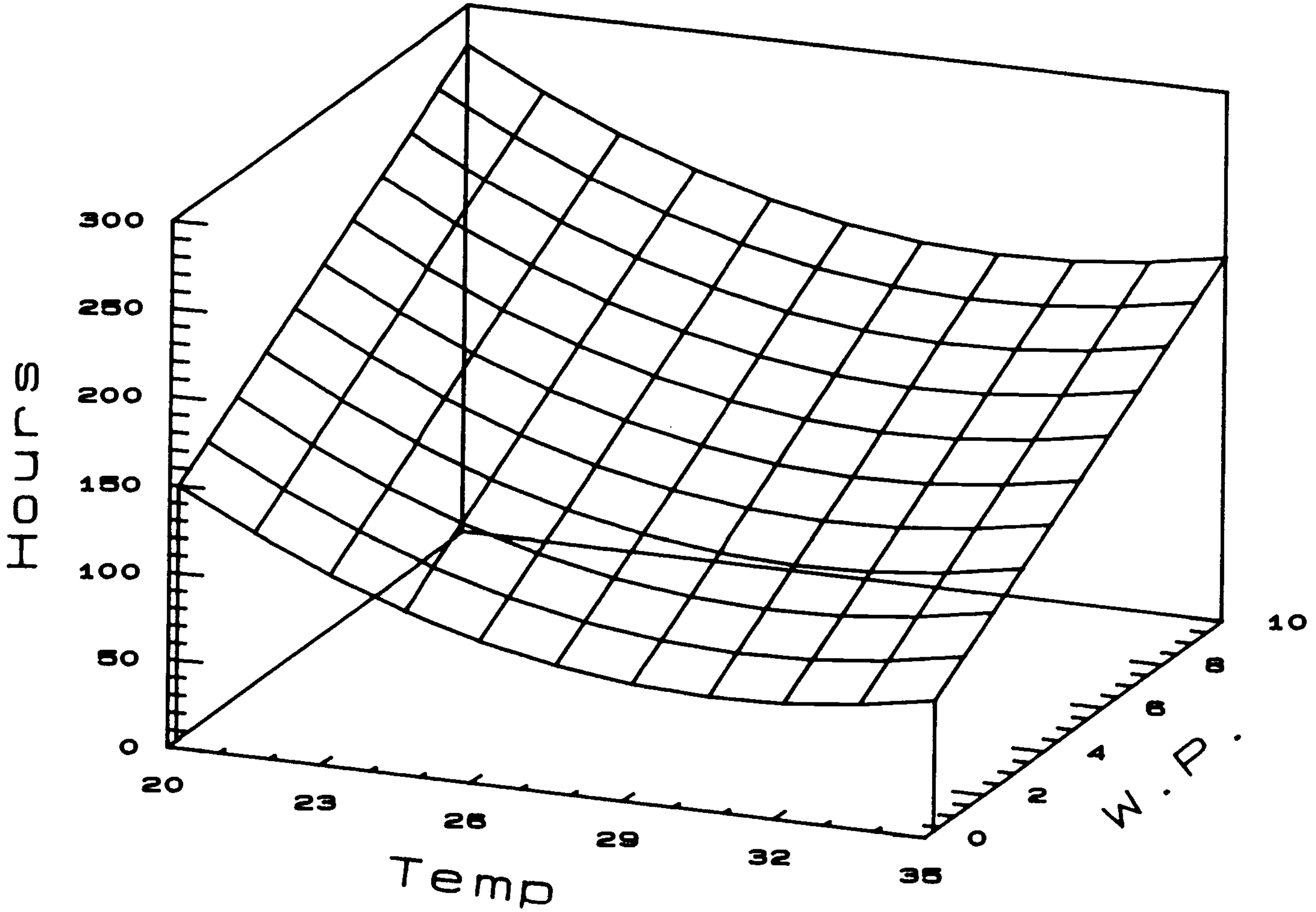

Figure 24: Polynomial response surface obtained with equation 22 showing emergence from 7cm of seeding depth as a function of temperature in ^{o}C and water potential in kPa.

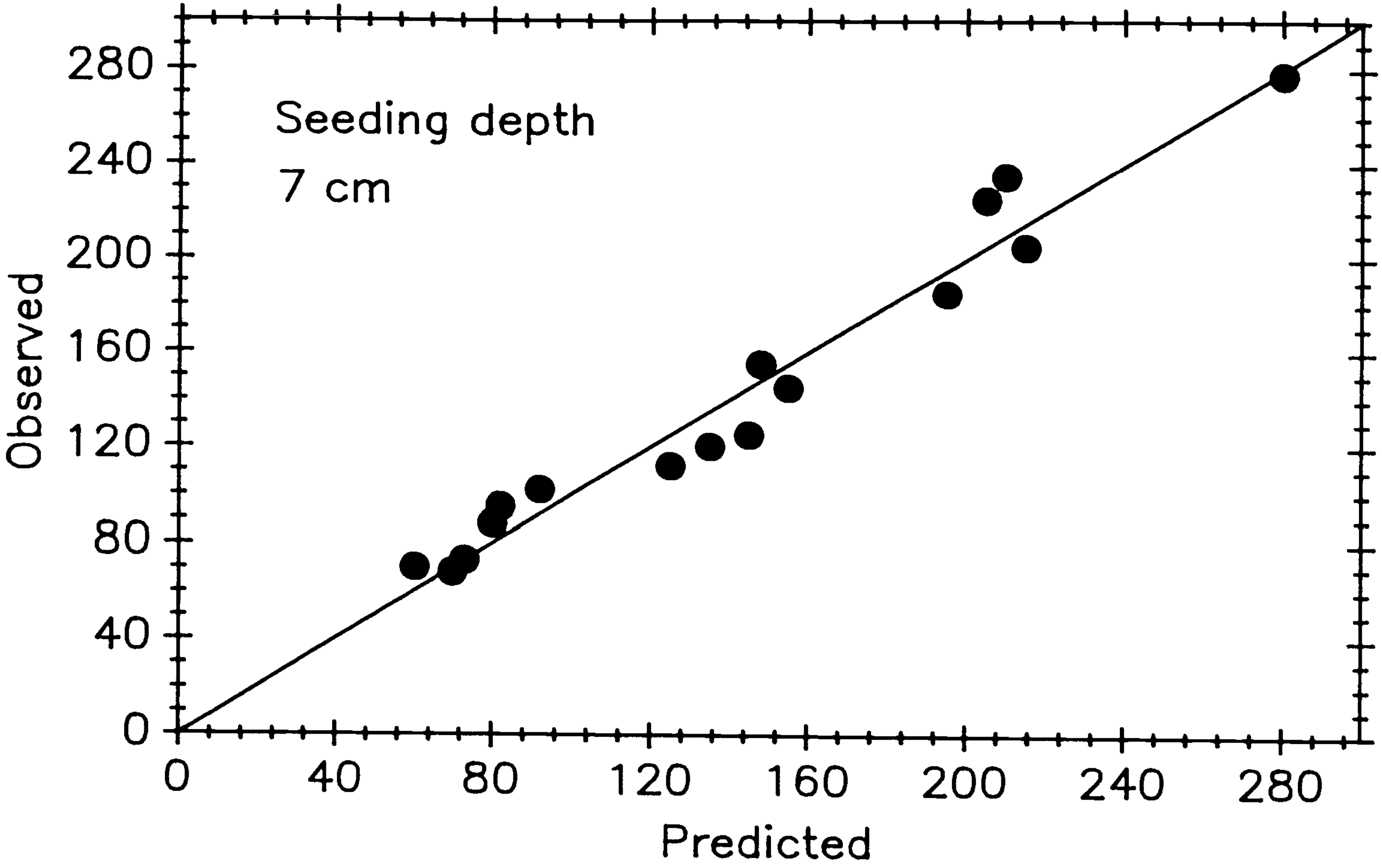

Figure 25: Plot of hours to obtain 80% emergence obtained with equation 22 versus observed values for the dependent variable.

Statistical analysis

In order to analyze the interaction between soil temperature, soil water potential, and seeding depth, a split-split plot design was used (Table 12). The variable compaction was discarded from the analysis because clearly it had no influence on time to emergence of corn.

The main effects of temperature, soil water potential, and seeding depth had significant F-values ($P<0.05$).

Differences in replications were non-significant, as occurred previously in the germination experiment. Blocking in this case was not effective in lowering the experimental error, because temperature was a constant factor in relation to that error. Interactions between temperature and seeding depth, also resulted in non-significant differences (Table 12).

Different results were obtained when means were compared at different temperatures. For example, using orthogonal contrasts, means for different temperatures at different seeding depths were compared (Table 13). The results show that the means for 20 and 30°C were significantly different, but means for 3 and 7 cm were not significant at that temperatures.

Table 12: Analysis of variance for split - split plot design using temperature as main plot and soil water potential and seeding depth as small plots.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Rep	2	61.5	30.7	0.3 NS
A(T)	3	95205.4	31735.1	322.4 **
Error	6	590.5	98.4	
B(SWP)	3	170218.2	56739.4	573.7 **
AB(TxSWP)	9	10264.3	1140.4	11.1 **
Error	24	2459.1	102.4	
C(SD)	1	19266.6		141.8 **
AC(TxSD)	3	411.7	137.2	1.0 NS
BC(SWPxSD)	3	11033.7	3677.9	27.0 **
ABC(TxSWPxSD)	9	2488.5	276.5	2.0 NS
Error	32	4347.3	135.8	

Coefficient of variation = 9.15%

Sy for means group 1 = 1.75 Number of observations = 32
Sy for means group 2 = 2.02 Number of observations = 24
Sy for means group 4 = 2.06 Number of observations = 24
Sy for means group 6 = 4.13 Number of observations = 6
Sy for means group 8 = 1.68 Number of observations = 48
Sy for means group 10 = 3.36 Number of observations = 12
Sy for means group 12 = 3.36 Number of observations = 12
Sy for means group 14 = 6.72 Number of observations = 3

Table 13: Orthogonal contrasts comparison for 3 and 7 cm of seeding depth, and 20 and 30°C.

T°C	20		30		L	$S^2 = \frac{L^2}{r.\Sigma k_i^2}$	F	
SD(cm)	3	7	3	7				
3cm vs 7cm	+1	-1	+1	-1	-62	302.3	2.3	NS
20 vs 30°C	+1	+1	-1	-1	166	2296.3	16.9	**
Interact. SD x T°C	+1	-1	-1	+1	-8.2	5.6	0.0	NS

SD = seeding depth

NS = no significant

** = highly significant

Compaction Experiment

As discussed previously the purpose of increasing compaction was to determine when soil compaction begins to be limiting for corn seedlings. The data show that seeds in the first treatment (0.1171 kg/cm^2) emerged uniformly in the shortest time; the second (0.3375 kg/cm^2) and the third treatment were delayed (Table 14).

Soil strength seemed to be the most important factor; the seeds germinated and the seedlings made considerable growth, but were unable to penetrate the surface layer. Coleoptiles and radicle tended to remain twisted and entrapped by both the surface and the sub-surface layer. As soil compaction was increased from optimum, the oxygen diffusion rate consequently decreased. As a result, both crust strength and oxygen diffusion rate may have been important for this non-uniform seedling emergence.

Whereas treatments 0.3375 kg/cm^2 and 0.5580 kg/cm^2, emerged non-uniformly, treatment 0.7812 kg/cm^2 did not emerge. Excessive compaction was detrimental, because high soil strength delayed or completely inhibited seedling emergence.

Statistical analysis

Table 15 shows the results of analysis of variance for this experiment.

Significant differences for compaction treatments existed. F values were higher than F table values ($P<0.05$).

Only the first three treatments were analyzed because of missing values.

Table 14: Treatments consisting of different static loads applied on compaction area of 36.29 cm^2. The last treatment did not produce emergence.

Static load	Equivalent	B.D	Emergence
kg	kg/cm^2	Mg/m^3	Hours
4.25	0.1171	1.36	140.5
12.25	0.3375	1.44	234.0
20.25	0.5580	1.49	348.0
28.25	0.7812	1.51	-

Table 15: Analysis of variance for compaction experiment.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Total	8	83529.5		
Compaction	2	58592.8	29296.4	7.0 *
Error	6	24926.7	4156.1	

* = significant 0.05%

V. SUMMARY AND CONCLUSIONS

Corn germination and emergence were evaluated by experiments that included the following soil physical parameters: soil temperature, soil water potential, seeding depth and compaction.

Three experiments were carried out. Each one covered a different objective. The objective of the first one was the determination of the range of influence of the main variables and determination of optimum temperature and optimum water potential. The second experiment had the purpose of studying the relationships among all variables and the third experiment was carried out for evaluating the effects of soil compaction.

Temperatures lower and higher than 30 °C increased the number of hours required for germination and emergence. At lower temperatures, higher activation energies and higher Q_{10} values were obtained. More energy was required to sustain physical and biological processes involved in germination, including water transport process.

The Q_{10} values and activation energies decreased when plotted as a function of decreasing water potential. The decrease was small and may occur because increasing water stress decreased the metabolic activity and therefore, the germination process.

The Arrhenius plot for the range of 20-30 ^{o}C showed a departure from linearity at about 25 ^{o}C, indicating that two different germination rates, were involved.

The data also showed that corn emergence is inhibited more by low temperature than by low soil water potential, until a certain level of water potential is reached where this relationship changes.

Below -500 kPa soil water potential was the main factor controlling germination and emergence. The most important factor for water absorption was the wetted seed-soil area of contact. Any reduction in this area reduced the rate of water uptake by the seeds and consequently delayed germination. This area is determined by water content as measured by matric potential.

Highly significant F-values were obtained for water potential, temperature and water potential-temperature interactions. No significant F-value was obtained for blocking, presumably because temperature was a constant variable. The same results were obtained for the rate of emergence experiment.

Seeding depth is of great importance. Time to emergence increased 20-30%, when seeding depth increased from 3 to 7 cm.

Slight compaction (bulk density = 1.36 Mg/m^3), had little effect because it did not increase significantly the seed-soil contact area and consequently time to emergence did not change. Excessive compaction (bulk density > 1.36 Mg/m^3) had a negative effect because high soil strength inhibited elongation and seedling emergence.

Models to predict germination and emergence at 3 and 7 cm of seeding depth were developed using multiple linear regression.

Use of the corn emergence model suggested in this manuscript along with long term measured or predicted temperatures, monthly weather outlook, and seeding depth will be useful in predicting probability of corn emergence at various planting dates.

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